HYDROGEOLOGICAL INVESTIGATION OF THE NAUKLUFT MOUNTAINS, SOUTHWEST NAMIBIA

A THESIS SUBMITED IN FULFILMENT

OF THE REQUIREMENT FOR THE DEGREE OF

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BY

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ABSTRACT

The Naukluft Mountains area is also referred to as the Naukluft Nappe Complex (NNC), that consist of northwest dipping carbonates and sandstones aged 750 Ma and form part of the Damara Super Group that has been thrust over the younger sedimentary rocks of the Nama Group, aged 550 Ma. In this study, three aquifers are characterized within the study area. First, is the Naukluft Karst Aquifer which is fractured and karstified, and partly underlies the surface run-off catchments of the Tsauchab and Tsondab ephemeral rivers; second is the Nama Aquifer, largely stratified aquifer with limited fractures to the east of the Naukluft Karst Aquifer and third, is the Namib Aquifer, which is a porous phreatic aquifer to the west and south of the Naukluft Karst Aquifer, confined to the alluvial formations of the Tsondab and Tsauchab ephemeral rivers. The Naukluft Karst Aquifer is a high rainfall and discharge area in terms of rainfall; however, in terms of recharge the volume of water available for groundwater recharge is low, due to high surface water discharge from the mountains. National average annual rainfall is 200 mm/a while the study area average is 170.36 mm/a based on the rainfall data collected from farmers during this study. Using the Chloride Mass Balance Method rainfall available for recharge is estimated to range from of 0.41 to 24.43 mm/a translating to 0.24 to 14.24% of received rainfall for the season of 2008/2009 calculated considering only wet deposition values for chloride. Places in the Naukluft Karst Aquifer area receive more rainfall and slightly higher recharge than calculated. Reconnaissance pumping tests were conducted in a well and boreholes at Leybank, Naukluft Park office, Zais and Solitaire to estimate transmissivity. Results indicate that transmissivity ranges from 4.1 to 23.1 m^2/d. storage coefficient was not estimated due to lack of piezometers during test pumping. The main groundwater flow is oriented along surface water drainages to the northwest and southwest, with minor flow to the northeast. Flow is controlled by elevation above sea level and structural geology of the Naukluft Karst Aquifer. A west-east trending groundwater divide is identified separating two distinct groundwater flows.

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ACRONYMS AND ABBREVIATIONS

Below a list of acronyms and abbreviations used in this report by order of appearance:

NNC:	Naukluft Nappe Complex
NRF:	National Research Foundation
DWAF	Department of Water Affairs and Forestry
MAWF:	Ministry of Agriculture Water and Forestry
CMB:	Chloride Mass Balance Method
SMZ:	Southern Margin Zone
D_5:	Deformation phase
^{18}O –	Heavy oxygen isotope
^{16}O	Light oxygen isotope
^{13}C	Heavy carbon isotope
^{13}C	Light carbon isotope
^{3}H	Heavy hydrogen isotope
(MgCO3)	Magnesite
(CaCO3)	Calcite
(CaMg(CaCO3)2)	Dolomite
GROWAS	National Groundwater Database
Q	Total discharge/pumping rate/Through flow
A	Cross sectional area
K	Permeability coefficient
Δl	Change in length
Δh	Change in hydraulic head
T	Transmissivity
K	Hydraulic conductivity
b	Aquifer thickness

W	Width
Tw	Transmissivity
Δl	Change in length
Δh	Change in hydraulic head
S	Storage coefficient
s	Drawdown
t	Time
r	Distance to the observation borehole
W (u)	Well function
ΔS	Change in Drawdown?
t_o	Time at the start of the pumping test
t	Time at the end of the pumping test
K	Hydraulic conductivity
Ss	Specific storage
q	Recharge flux
p	Average annual rainfall
Clwap	Concentration of chloride in precipitation
Clgw	Concentration of chloride in groundwater
TDS	Total Dissolved Solids
EC	Electrical Conductivity
δD	Deuterium isotopic composition notation
per mil	Concentration in parts per thousand
mg/l	Milligrams per litre
GIS	Geographical Information System
ASTER	Advanced Space Borne Thermal and Emission Radiometer
SRTM	Shuttle Radar Terrain Model

DEM	Digital Elevation Models
HNO3	Nitric acid
mm	millimetre
ºC	Degree centigrade
ml	Millilitre
pH	Hydrogen potential of a solution, water or aqueous medium
DO	Dissolved oxygen
ICPMS	Coupled Plasma Mass Spectrometry
CFCs	Chlorofluorocarbons
TPA	Test pumping Analysis Software
OML	Otavi Mountain land
SMOW	Standard Mean Ocean Water

ACKNOWLEDGMENTS

Heterogeneity in the aquifers prompts further investigations to better understand aquifer systems and their properties. The beauty of the Naukluft Nappe Complex (NNC) is that even though critically acclaimed scholars have published scientifically renowned work, very little is known with regard to its groundwater systems and how its complex geology influence the groundwater systems.

This study is one of the first works of its kind to be done in the Naukluft Mountains as part of the inter-University and multi-disciplinary Naukluft Nappe Complex Project, funded by the South African National Research Foundation (NRF) was led by Dr. Jodie Miller and Prof. Benjamin Mapani with associates Prof. Torsten Venneman and Dr. Christie Rowe whose guidance is most valued and appreciated.

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DECLARATIONS

I, Winnie Nansunga Kambinda, declare hereby that this study is a true reflection of my own research, and that this work, or part thereof has not been submitted for a degree in any other institution of higher education.

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CHAPTER 1: INTRODUCTION

1.1 PHYSICAL ENVIRONMENT

The Naukluft Mountains form part of the Namib-Naukluft National Park, and extends over 50, 000 km^2 with the Sossusvlei dunes as the main attraction. Figure 1-1 shows a map of the study area, the extent of the Naukluft Mountains, the location of the boreholes sampled in 2008 and 2009 as well as the location of boreholes sourced from GROWAS. The National Park is sparsely vegetated with different plant species, some of which are endemic to this part of the world. The Tsauchab and Tsondab rivers which originate from the mountains are west flowing ephemeral rivers draining towards the Namib Sand Sea into Soussusvlei and Tsondabvlei respectively. The area is sparsely populated with high density populations distributed more towards Sesriem and Solitaire. On an economic perspective, the Naukluft is a booming touristic destination. Guest farm establishments, livestock and game farmers have seen an upsurge of tourist activity. Activities in the Naukluft area have increased; there is now a well-established water bottling company at Farm Neu Onis and a vineyard near Tsuachab river area; there is an increase in water demand and supply in the area (Joint Venture 2010).

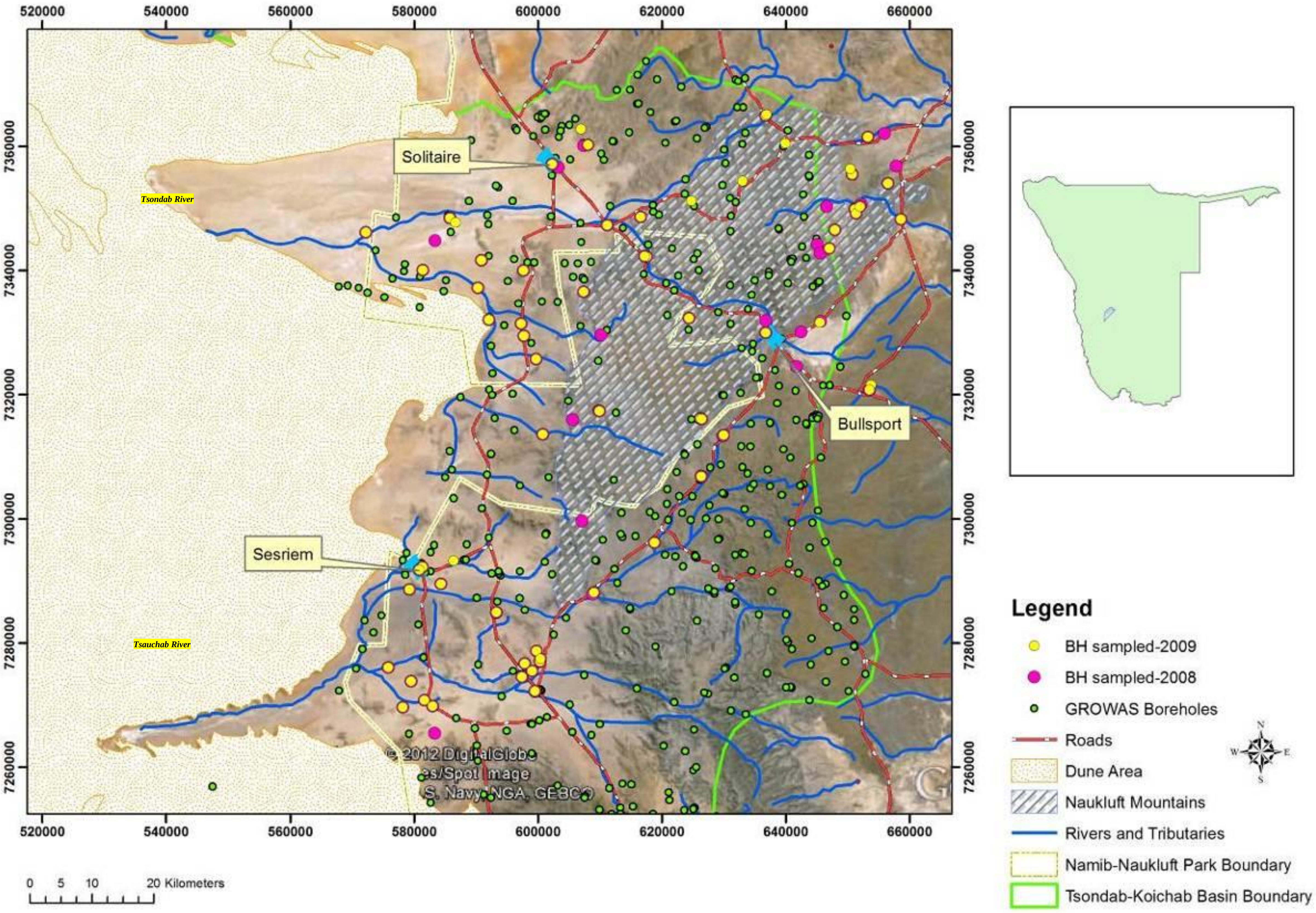


Figure 1-1: Map of the Study Area Showing Sampling Sites

The aquifers of the Naukluft Mountains are dominated by fractured and karstified dolomite and limestone of the Damara Sequence emplaced onto sediments of the Nama Sequence in a nappe structure. Alluvial aquifers in ephemeral rivers are very good groundwater sources and they continue to supply water to the area. The entire Namib Desert is considered to have very poor potential for recharge and all the rivers along the coastal region therefore have a very low abstractions rates potential. Current limitations on water supply has seen a shift from just domestic and livestock farming towards increased development in the region especially tourist establishments. As mean rainfall in the region of the Namib Sand Sea is less than 100 mm/a, an indication that rainfall is not sufficient to recharge the aquifer system, hence over-abstraction could be a constant threat. As part of the wider Tsondab-Koichab Basin the aquifers in the Naukluft Mountains are rather strategic as water demand projections by Joint Venture Namibia (2010) indicate that there will be a drastic increase by year 2030.

1.2 TSONDAB-KOICHAB HYDROGEOLOGY

Namibia is subdivided into eleven Water Basins, (Figure 1-2) (BIWAC, 2004). Demarcation was done utilizing digital data collected from various sources. The main criterion for demarcation of national basins was on the basis of surface and groundwater catchments of large river systems (BIWAC, 2004). The Tsondab-Koichab Basin is the main national basin in which the Naukluft Karst Aquifer is situated. Based on BIWAC’s (2004) demarcation, the Tsondab-Koichab Basin is framed by the Kuiseb Basin to the north, the Orange-Fish Basin to the east and south and by the Atlantic Ocean to the west. The eastern boundary of the basin follows mainly the surface water divide; which is roughly the water divide between the Kuiseb and the Tsondab rivers (Christelis & Struckmeier, 2001). The surface and groundwater drainage is directed towards the Atlantic Ocean (BIWAC, 2004).

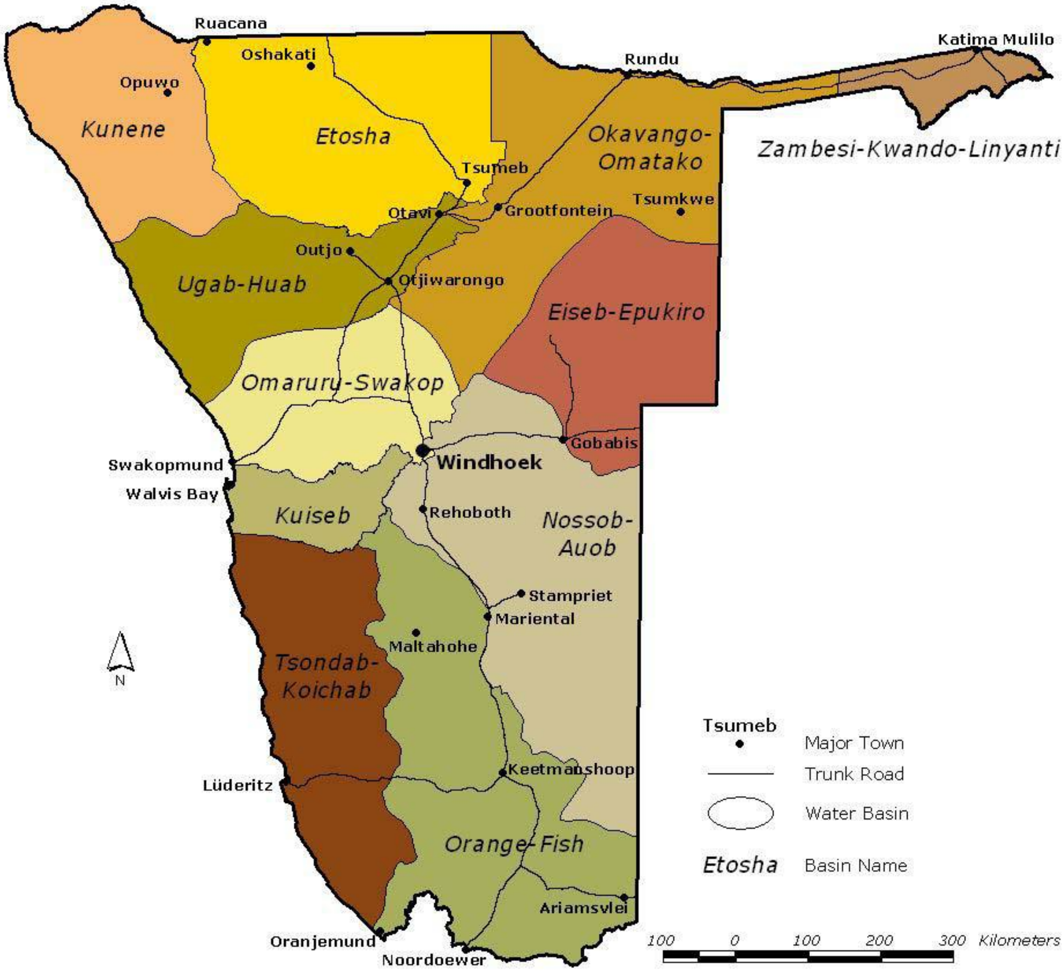


Figure 1-2: Eleven Water Basins of Namibia (After: Bittner, 2004)

Most of the land in the basin is declared as a national park or private conservancies or protected areas so as to protect the desert environment (BIWAC, 2004). The Namib Sand Sea lies between the Kuiseb River and the Aus-Luderitz Road and forms part of the Namib-Naukluft National Park whereas the area between Luderitz and Oranjemund are part of the Sperrgebeit, a Diamond Protected Area. As a result the town of Luderitz is the most populous in the basin while several centers such as Aus, Sesriem and Solitare are tourist hubs.

1.2.1 AQUIFER CHARACTERIZATION

The Namib Desert receives limited rainfall and like the rest of the Namibian interior; surface water is not a permanent feature. Aquifers in the basin whose potential in shown in Figure 1-3 are a reliable source of water supply and they are classed as follows:

- ***Karst Aquifers:*** These are mainly the heavily karstified Naukluft Karst Aquifer (Christelis & Struckmeier, 2001) situated in the northwest of the basin. This type of aquifer is generally of good yield and water quality and is the main focus of this study;
- ***Alluvial Aquifers*****:** Christelis & Struckmeier (2001) highlight the significance of alluvial aquifers and in the desert environment in that they are closely linked to perennial, ephemeral or even fossil rivers. These would be the alluvial aquifers of the Kuiseb River in the north, the Tsondab and Tsauchab Rivers in the southwest and central areas and the Koichab and Tsaris rivers in the south. While the Kuiseb River flows into the Atlantic Ocean the Tsondab, Tsauchab, Tsaris as well as the Koichab Rivers are what Christelis and Struckmeier (2001) describe as ‘Endorheic Rivers’ that terminate against the Namib Sand Sea today but flowed to the ocean in the past resulting in the formation of palaeo-river channels beneath the dunes. Surface water infiltrates these paleo- river channels there by discharging into the ocean (Christelis & Struckmeier, 2001). Alluvium of the Tsondab and Tsauchab rivers is of moderate yield (Christelis & Struckmeier, 2001) and much like the karst aquifer their potential is yet to be studied in great detail. Currently, they supply tourist establishments and livestock farms around the Naukluft area. The Koichab alluvium have higher yields compared to the afore mentioned river systems. Christelis & Struckmeier, (2001) relay that well fields in the Koichab pan which supply the town of Luderitz have a yield range of 5 m^3/h to 50 m^3/h with ages from 5 000 to 7

000 years old. Koichab pan water is considered fossil (Joint Venture Namibia, 2010) and very old water has been dated to be 13,050 thousand years old south of the Naukluft Mountains by Bernhard (2009);

- ***Bedrock Aquifers***: It is reported by Christelis & Struckmeier, (2001) that bedrock aquifers are very limited. Around the Naukluft area, the borehole at Panaroma is assumed to be drilled in basement fractures and some areas that are in the south of the mountains like the Batesda desert homestead are in a fault zone (the Hebron Fault) and a few boreholes in the weathered regolith of crystalline basement rocks of the Mooi River Formation. (Christelis & Struckmeier, 2001) site the small town of Aus as an example in the basin whose growth is hampered due to insufficient water resources. Local aquifers of limited extent are found in fractured zones of gneisses and granites and yield lowly in the range of 1 m^3/h to 5 m^3/h.

1.2.2 GROUNDWATER UTILIZATION

Long-term sustainable yield of Namibia’s groundwater is quoted at 300 Mm^3/a (Joint Venture Namibia, 2010) of which the resources in the basin make a relatively small fraction.

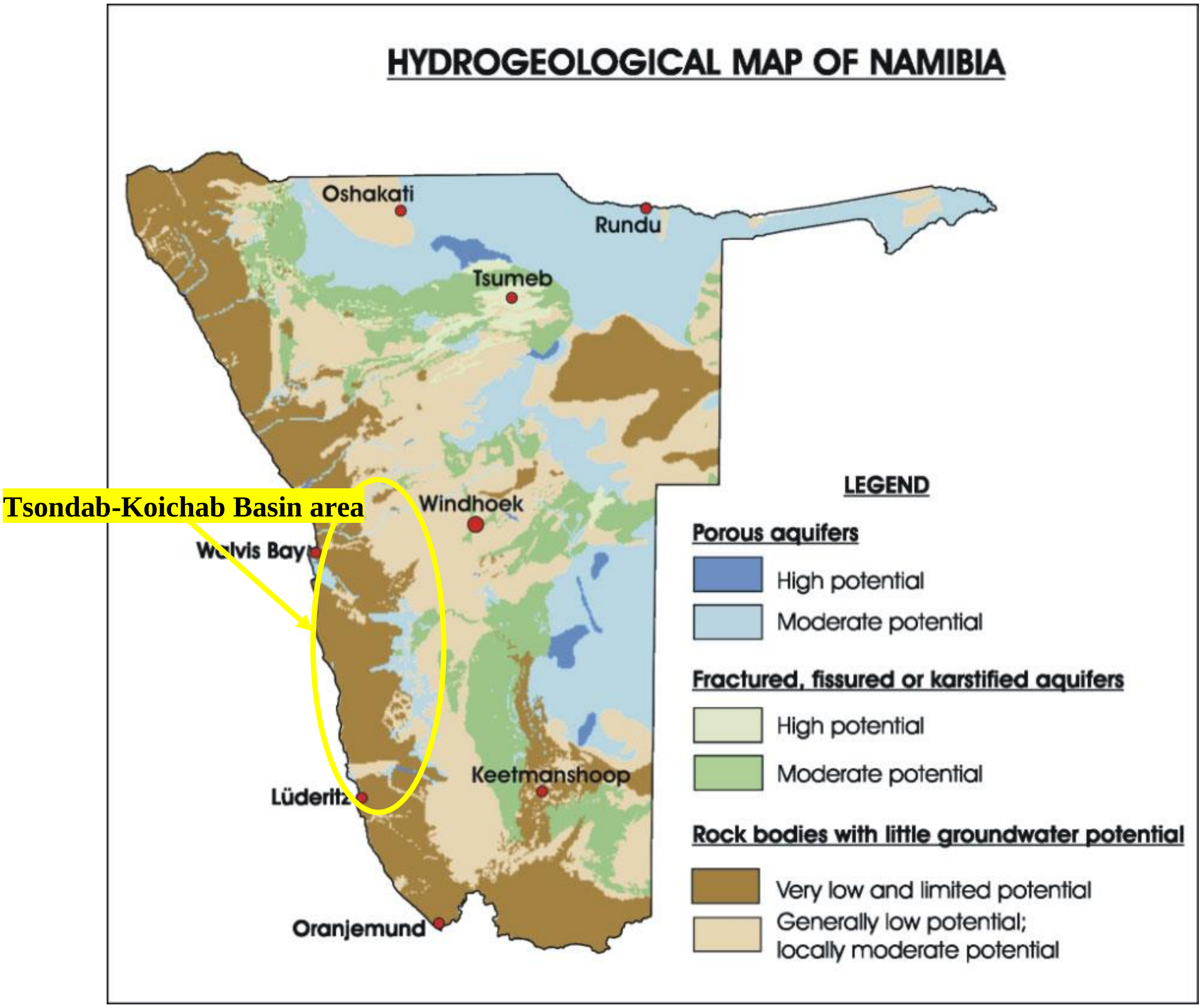


Figure 1-3: Simplified Hydrogeological Map of Namibia (After: Christelis & Struckmeier, 2001)

Most strategic aquifers such as the Koichab, Tsaris, Tsondab and Tsauchab rivers as well as the Naukluft Karst Aquifer are the most utilized and have the best groundwater potential in the basin. Basement aquifers in the region as stated above tend to be low yielding and as such have not been targeted for water supply except in cases of local supply.

CHAPTER 2: LITERATURE REVIEW

This section elaborates on general flow of water, carbonate aquifers, groundwater flow in an aquifer, rainfall in the study area and recharge. Further studies that have been completed in the Naukluft Mountains are discussed.

2.1 THE HYDROLOGIC WATER CYCLE

The hydrologic water cycle (Figure 2-1) is a universal account of the earth's waters. Heath (1983) refers to the cycle as a constant movement of water above, on and below the earth's surface, driven by processes such as precipitation (rainfall, snow, etc.), over land and run off, infiltration, groundwater base flow and evaporation. Each process is governed by its onset of physical parameters. This study focuses on groundwater, an important component of the hydrologic cycle through which aquifers such as carbonate and alluvial aquifers are defined.

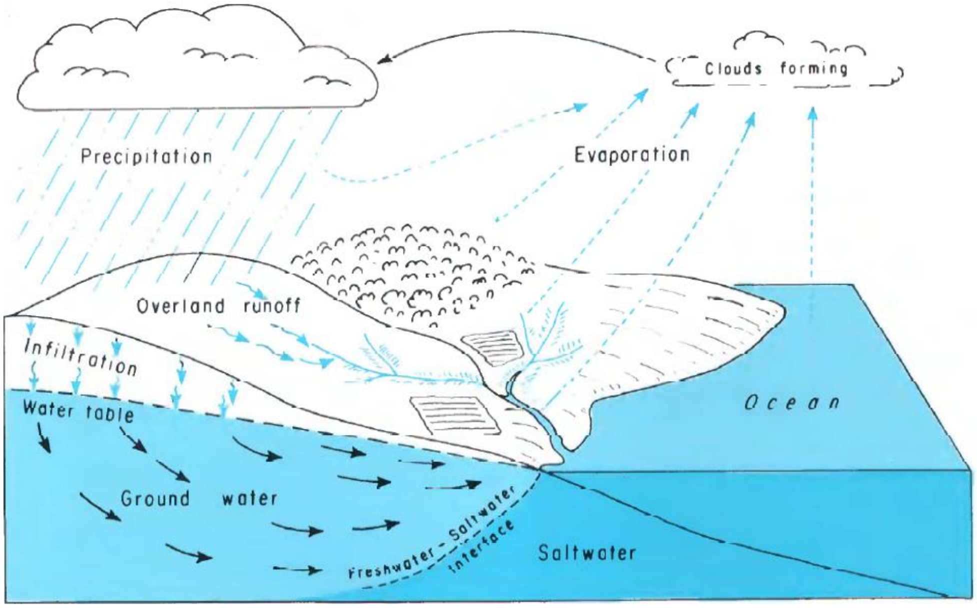


Figure 2-1: Hydrogeological Cycle. (After: Heath, 1983)

2.2 CARBONATE AQUIFERS

Carbonate aquifers are one of the very reliable aquifer types but, due to their geomorphology they can also be very complex and vulnerable especially to contamination from surface activities. Carbonates are not primary aquifers, they are hard rocks that without fracture zones and karstification conduits cannot store and transmit water. Deer et al (1996) looked at carbonates from a mineral constituent point of view; they defined carbonates as rocks that are composed of minerals in which the essential structure unit is the CO_3^{-2} ion. Some of the most common forms are Magnesite ($MgCO_3$), Calcite ($CaCO_3$), Siderite ($FeCO_3$) and Dolomite ($CaMg(CaCO_3)^2$). Carbonates as sedimentary rocks that are derived from within the basin in which they accumulate and are therefore intra-formational and most certainly intra-basinal deposits (Pettijohn, 1975). The observation made by Pettijohn (1975) is used to differentiate between the Otavi Mountain Land (OML) carbonates in northern Namibia to those of the Naukluft Mountains. This is because unlike the carbonates of the OML, the Naukluft carbonates are material that have been transported and re-deposited, a process Pettijohn (1975) terms allochtonous (without roots). In addition the Naukluft Mountains are tilted as a consequence of their emplacement. Whereas the carbonates of the OML and other parts of the country such as those found in Kaoko and Gariep Belts in the northwest and southwest respectively, have not experienced movement but are in-situ deposits with well-defined stromatolitic or growth bedding (Pettijohn, 1975). It should be noted however, that these textures are not observed in metamorphosed carbonates.

Limestone can be grouped into six classes, grainstones, boundstones, carbonate mudstones, alladapic limestones, dolomite as well as tufa and travertine. Each class is described by Pettijohn (1975) as having different characteristics based on their formation. The first class is grainstone and they are marked by a framework of pore system, a product of current action of coarse debris mechanically deposited and emplaced in the fabric of the rock; the second class is boundstone and these on the other hand are composed of coarse biogenic framework bound together during accumulation by encrusting algae, the whole rock mass is marked by large internal voids in which internal sedimentation is common. The third class are carbonate mudstones which are predominantly fine-grained matrix with few layer components and in some cases no larger constituents. The fourth class are the allodapic limestones, that differ from the previous classes by being re-sedimented carbonate material moved from their place of origin to deeper water by turbidity currents. Dolomites are the fifth class and are the most common diagenetic carbonates. They maybe replacements of other carbonates. The last class is tufa and travertine deposits; that are formed from river waters and evaporating springs. According to Pettijohn (1975) they are spongy porous material that form a thin surficial deposit about springs and seeps and are exceptionally represented in rivers. Tufa deposits are more porous and are deposited in rivers at ambient temperatures, while travertine deposits are deposited in springs and are less porous. Both deposits are a common feature in the Naukluft Mountains.

Carbonates make an interesting geologic subject, with their complex nature, even more so as aquifers. This is because questions on hydraulic dynamics are not easily approached or solved and therefore assumptions are made to account for uncertainties. Flow dynamics, through the many networks of karst pathways are not as straight forward as primary aquifers. As aquifers, carbonate rocks are referred to as karst aquifers which White (2002) defines as those that contain dissolution-generated conduits that permit the rapid transport of groundwater often in turbulent flow. The conduit system receives localized inputs from sinking surface streams and from run off through sink holes.

Understanding properties, characteristics and evolution of karst aquifers has substantially improved (White, 2002). In Namibia, recent studies seem to focus on understanding the hydrodynamics of karst aquifers and there is still much to be done. White (2002) in his work further adds that progress has been made in the use of water budgets, tracer studies, hydrograph analysis and chemography analysis for characterization of karstic aquifers. The author however sees that more progress is needed in:

a) Construction of models that describe the complete aquifer including the interactions of all components;

b) Models for clastic sediment transport within the aquifer; and

c) Working out processes and mechanisms for contaminant transport in karst aquifers which will update the conceptual framework.

The situation in Namibia is testament to the point that White (2002) brings across, this is because karst aquifers still need to be holistically studied for one reason or the other.

Different authors for example; Kovács et al (2005), Long and Putnam (2004) and Quin et al (2006) have investigated karst aquifers with a focus on different questions, while in some cases using the same tools while others have used the opportunity to study karst phenomena to test hypotheses and new tools.

Kovács et al (2005) took interest in karst aquifer classification and in their work used spring hydrographs to determine aquifer characteristics, aimed at quantifying the hydraulic and geometric properties of a karst aquifer and its global responses in order to facilitate distributive groundwater flow model. Kovács et al., (2005) states that a simple conceptual model of karst systems consists of a rectangular aquifer shape, regular network of high conductivity karst conduits embedded in low permeability fissured rock matrix and a simple karst spring that drains the conduit network. Further, Kovács et al (2005) states that limited information on geometry and hydraulic properties can be provided from hydrographs. Their study (Kovács et al, 2005) demonstrated that spring hydrograph recession coefficient (α_b) calculated based on the quantitative method adopted for the study, is an important parameter in terms of determining geometric and hydraulic parameters.

Long and Putnam (2004), use ^{18}O a natural tracer to study groundwater flow in the Madison Karst Aquifers situated in Black Hills of South Dakota, USA. They used an ^{18}O time series to model distinct responses and relative proportion of conduit, intermediate and diffuse flow. The study showed that in karst aquifers flow may branch apart and rejoin as a result of anastomosing karst networks. Quin et al (2006) on the other hand, investigated complex groundwater flow in a karst aquifer situated in Hohenfels, Germany. Karst terrain is assumed to be a mixed flow system with interacting components of diffuse and conduit flow (Quin et al, 2006). With a study area where karst terrain is dominant, with a network of ephemeral river valleys and topographic relief, it was demonstrated that numerical methodology can be used to model heterogeneities of flow in karst environment by assessing a sequence of adjacent cells with drains to simulate conduits.

Dafn et al (2010) examined the influence of geological structure such as folding and lithology on groundwater flow and the influence that the karst system bears on groundwater flow. One relates the study question to the situation in the NNC, which has complex structural orientation. Dafn et al (2010) utilized a 3-D geological base grid implemented into a numerical code. The study observed that as groundwater flow quantities increase, the hydraulic conductivity also increases which the authors' link to the karstification mechanism. It was also observed that where groundwater flow lines converged and where discharge increased the karstification process intensified and permeability increased. Dafn et al (2010) reported that the above observations are as a consequence of the mountainous region along the syncline axes where groundwater flow lines converge, higher conductivities were found. What the model exhibited was that in low land confined areas, the geology structure does not play a major role in directing groundwater flow but is rather controlled by a well-developed karst system and relatively homogeneous carbonate system. This implies that in areas where carbonate rocks are deformed, the geological structure has an influence. Therefore, geological structure has an influence on an area likely to have a much higher density of fractures; namely zones where stresses are highest, whereas low stress zones will remain more or less intact over a long time. This also promotes strain partitioning should further deformation occur, ensuing in a zone of karstification that serves as the fluid conduit zone.

Groundwater flow in aquifers is governed by parameters and processes; these are related to the aquifer’s physical orientation and extent. Aquifers are either primary or secondary, and each type transmits and stores waters in either primary or secondary openings or voids and conduits (Figure 2-2). Heath (1983) states that; porosity, hydraulic head, gradient as well as hydraulic conductivity is key elements of groundwater flow and storage.

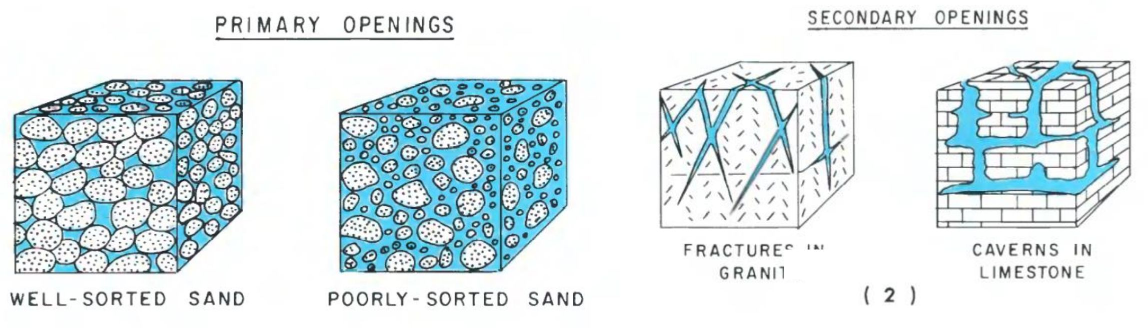


Figure 2-2: Primary and Secondary Porosity in Aquifers (After: Heath, 1983)

Porosity is the ratio of openings to the total volume of the rock. It is important because it defines the maximum amount of water that an aquifer can contain (Heath, 1983). Hydraulic head and gradient are related to the direction and slope of the water table and indicate the direction of groundwater movement (Heath, 1983). Hydraulic conductivity on the other hand, depends on the size and arrangement of water transmitting openings as well as on the dynamic characteristics of the water; it can also be different in different directions (Heath, 1983).

2.3 FLUID FLOW

Mezor (2004) describes water flow processes in an unconfined permeable system in the points outlined below and illustrated in Figure 2-3

- Runoff: this occurs when rainfall, falls over the surface of the system. This is divided between infiltrating water and runoff water. Runoff water is focused to the valleys and riverbeds, while infiltrating water is into areas of increased infiltration rates and thus increased recharge rates.
- Infiltration and evapotranspiration: in this process the infiltrating water is partially returned to the atmosphere by evaporation and evapotranspiration of water that is retarded on the surface and in the soil zone. The other portion of water that enters the saturated zone as recharge.
- Recharge: in this process portion of infiltrating water that reaches the saturated zone is the recharge. Zone of through-flow., where water flows through voids in the rocks, and eventually is discharged at a terminal base of drainage. Through-flow occurs in the zone of hydraulic potential differences, that is, between the topographic relief and the terminal base of drainage at which the hydraulic potential is zero. Flow in this zone is vertical down flow and lateral overflow.

- Zone of groundwater stagnation: At depths below sea level all the rock systems of the continents are filled with water to their full capacity.

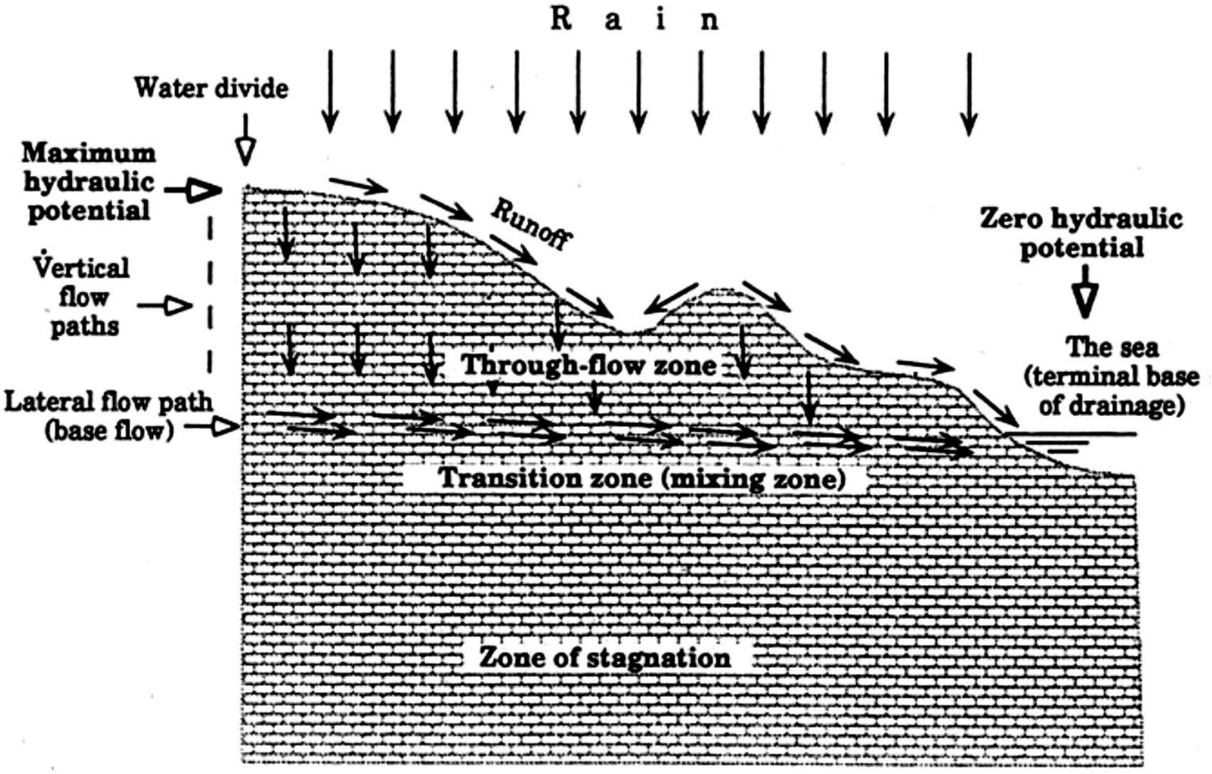


Figure 2-3: Water Flow in an Unconfined Permeable System (Mezor, 2004)

Fluid flow in aquifers is defined by Darcy's Law. Derived by Henry Darcy in 1856 (Heath, 1983) as follows:

The law states that:

Q = -KA (Δh/Δl) **Equation 1-1** (Heath, 1983)

Where **Q** = Total discharge, **A** = Cross sectional area, **K**= Permeability coefficient

Δl = Change in length & **Δh** = Change in hydraulic head.

According to Darcy, groundwater flow is laminar, that is; particles tend to follow discrete streamlines and do not mix with particles that are in adjacent streamlines (Heath, 1983).

Darcy’s law can be applied to determine aquifer transmissivity, which Heath (1983) defines to be the capacity of an aquifer to transmit water of a prevailing kinematic viscosity.

$\mathbf{T = Kb}$ **Equation 1-2** (Heath, 1983)

Where $\mathbf{T}$ = Transmissivity, $\mathbf{K}$ = Hydraulic conductivity & $\mathbf{b}$ = aquifer thickness

Darcy’s Law can only be applied for laminar flow and in validating its application a dimensionless number Reynolds number (Re) used if fluid dynamics is employed.

Haitjema (1995) states that the definition of the Reynolds number depends on the character of the flow problem. In the case of the Naukluft Mountain Darcy’s Law would not apply as flow is turbulent, is confined to fracture zones, fault zones, sinkholes and cavities. In this case

$\mathbf{Re\ (rock) = d\upsilon/\nu}$ **Equation 1-3** (Haitjema, 1995)

Where $\mathbf{d}$ = fracture aperture, $\boldsymbol{\upsilon}$ = average groundwater velocity & $\boldsymbol{\nu}$ = kinetic velocity of groundwater

In the case of flow through sand and gravel aquifers

$\mathbf{Re\ (soil) = Dq/\nu}$ **Equation 1-4** (Haitjema, 1995)

Where $\mathbf{D}$ = average grain diameter, $\mathbf{q}$ = specific discharge.

For laminar conditions in a fracture Re (rock) should be less than 800 while for laminar flow conditions to be assumed in sand and gravel aquifers Re(soils) should be less than 1 (Haitjema, 1995).

Ahmed & Salih (2008), report that laminar flow in fractured aquifer is assumed to occur in a fractured aquifer especially if groundwater flow is calculated from single fractures. Withersoon et al (1979) states that hydraulic conductivity (K_f) of the fracture, with a 2b aperture is defined by:

$\mathbf{K_f = (2b)^2\gamma/12\mu}$ **Equation 1-5 (**Ahmed & Salih, 2008).

Where **2b** = fracture aperture, γ = specific weight of water and μ = viscosity.

If the flow is steady state and isothermal the flux per unit drop in head can be developed from Darcy’s Law which Witherspoon et al (1979) simplifies forming a basis for the cubic law:

$\mathbf{Q/\Delta h = C(2b)^3}$ **Equation 1-6** (Ahmed & Salih, 2008)

The cubic law according to Bäumle (2003) proves to better describe the groundwater flow in fractures than Darcy’s law, further noting that double-porosity or single fracture models must be taken into consideration in order to evaluate hydraulic tests.

Heath (1983) expresses transmissivity in terms of Darcy’s law to calculate the quantity of water (through flow) moving through a large width of an aquifer as follows:

$\mathbf{Q = TwW\ (\Delta h/\Delta l)}$ **Equation 1-7** (Heath, 1983)

Where **Q** = Through flow, **W** = width, $\mathbf{T_w}$= Transmissivity, Δ**l** = Change in length &

Δ**h** = Change in hydraulic head

The capacity of the aquifer to store water is equally important. This is represented by the storage coefficient which Heath (1983) defines to be the volume of water that an aquifer releases into storage per unit. This unit is expressed in Equation 1-4.

S = volume of water/ (unit area) (unit change in head) **Equation 1-8** (Heath, 1983)

Estimation of aquifer parameters is almost always supported by pumping tests and test data evaluation. The principle of a pumping test is simplified by Kruseman and de Rider (1991), who say that if water is pumped from a borehole and discharge is measured in the borehole and the observation boreholes at a known distance, the measurements taken can be fitted into an appropriate equation and calculate hydraulic characteristics of an aquifer.

Before the pumping test is conducted the following details must be known about the aquifer:

- Geological characters of the sub-surface (all lithological, stratigraphic and structural features that may influence flow);
- Aquifer type and confining beds;
- Barriers of impermeable materials; and
- Any lateral recharge boundaries (Kruseman and de Rider, 1991).

Pumping test field measurements (drawdown and recovery) are taken at pre-determined intervals which can be tailor made to the level of data needed for the analysis. The duration of the tests can range from several hours to days depending on the level of data needed.

In Table 1-1 below after Kruseman and de Ridder (1991) list the range of intervals that water level measurements should be taken in the pumping borehole during the pumping test

Table 1-1: Range of Intervals Between Water level Measurements (After Kruseman and de Ridder, 1991)

Time Since Start of Pump	Time Interval
0 – 5 minutes	0.5 minutes
5 – 60 minutes	5 minutes
60 - 120 minutes	20 minutes
120 – shut down	60 minutes

The Theis Method of calculating transmissivity and storativity according to Heath (1983) was amongst the first derived formulas developed to calculate aquifer parameters, developed by C. V. Theis in 1935. Several assumptions were made as follows:

- Transmissivity of the aquifer tapped by the pumping well is constant during the test to the limits of the cone of depression;
- The water withdrawn from the aquifer is derived entirely from storage and is discharged instantaneously with decline in head; and
- The discharging well penetrates the entire thickness of the aquifer and its diameter is small in comparison with the pumping rate so that storage in the well is negligible.

Therefore the equation used to determine transmissivity and storage coefficient was derived as follows:

$T = QW(u)/4\pi s$ **Equation 1-9;** and

$S = 4Ttu/r^2$ **Equation 1-10.**

Where **T** = transmissivity, **S** = storage coefficient, **Q** = pumping rate, **s** = drawdown
t = time, **r** = distance to the observation borehole & **W(u)** = well function.

Because the equations could not be solved directly, a graphic method was derived. Data plot of drawdown versus time is matched to the type curve of W(u) versus 1/u. At a convenient point on the over lapping part of the sheet containing the data plot and type curve values s, t, (or t/r^2), W(u) and 1/u are noted and substituted in the equation (Figure 2-4).

From the Theis Method, C. Jacobs (1946) derived the following equation to determine transmissivity and storage coefficient from time-drawdown graphs:

$T = 2.3Q/4\pi\Delta s$ **Equation 1-11**; and

$S = 2.25sTt_o/r^2$ **Equation 1-12.**

Where **T** = transmissivity, **S** = storage coefficient, **Q** = pumping rate
ΔS = drawdown, $\mathbf{t_o}$ = time & **r** = distance to the observation borehole.

This method differs from Theis Method because it applies to the zone where the cone of depression occurs and steady state conditions have developed (Heath, 1983).

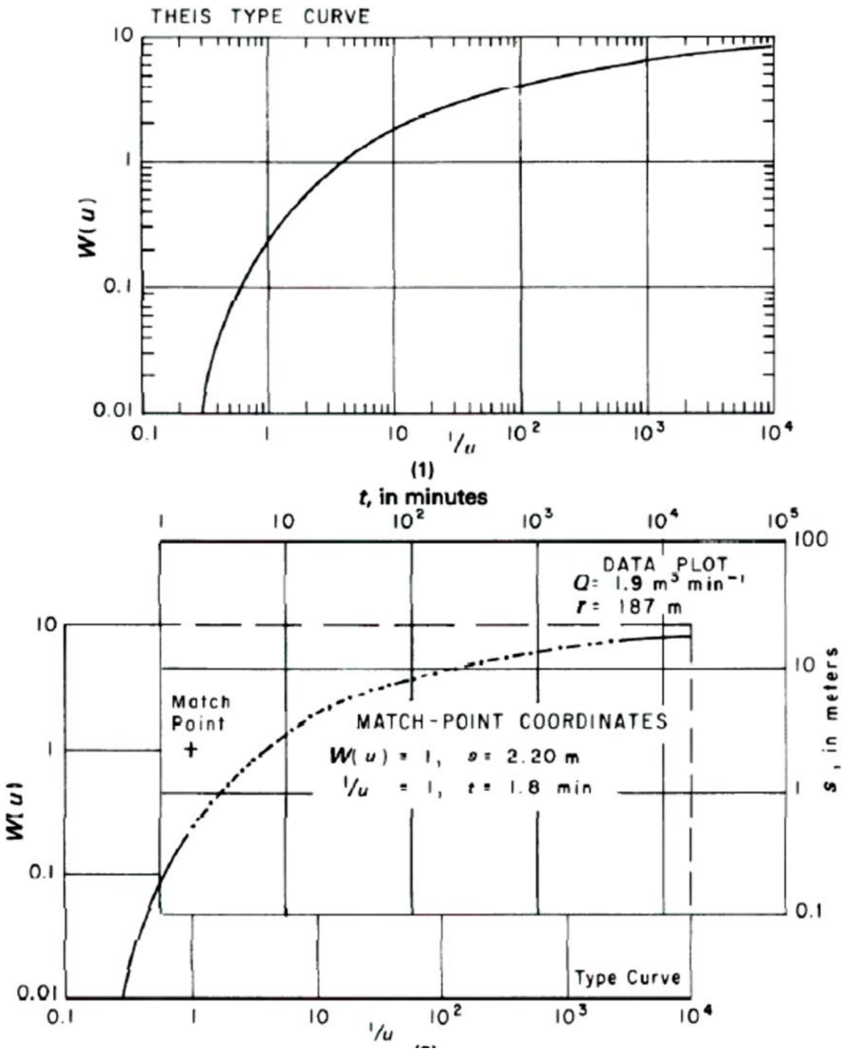


Figure 2-4: Graphic Solution for the Theis Method (After: Heath, 1993)

In Tokyo, Japan; pumping tests using multi-screen pumping boreholes and multi-level piezometers were carried out for groundwater flow control in a large-scale excavation site. Changes in groundwater pressure head were measured from pumping boreholes and hydraulic conductivity (K) and Specific storage (S_s) were estimated using the Cooper-Jacob method and later calibrated with a fine element method (Miyak et al, 2008).

Leven and Dietrich (2006) in their study compare pumping test configurations using sensitivity coefficient. The coefficients are a measure of the relationship between a change in drawdown and a change in the parameter distribution, allowing analysis of intrinsic characteristics of pumping test in order to better understand their response to aquifer heterogeneity by carrying out single and dual pumping tests. By means of sensitivity coefficients it was shown that the spatial assignment of estimated parameters is much simpler for single-well than for two-well pumping tests.

Kollet and Zoltnik (2005) show in their study on the influence of aquifer heterogeneity and return flow on pumping test data interpretation; that aquifer heterogeneity has an effect on pumping test and the interpretation of data collected. They present analysis of time-drawdown data from pumping test carried out on a cluster of boreholes. The results showed that aquifer heterogeneity appears to be an important reason for large variations in estimates for specific yield and vertical hydraulic.

Pumping tests are also used as a means of correcting and calibrating flow model estimates. As Bodin et al (2012) shows in their study on a karst aquifer in France, where a comparison of alternative modeling approaches against real world field experiments. This approach according to Bodin et al (2012) has proven to be fruitful in advancing the state of the art in modeling fractured media. de Smedt (2011) analyses pumping test data to develop an analytical solution for constant rate pumping tests in fissured porous media.

The present study will analyze pumping test data from the first reconnaissance pumping test done in the study area in 2009 by Fabian May (Stellenbosch honors student) and myself. Aside from the preliminary test pumping, there has been no analysis and evaluation of the data collected during 2009 to determine aquifer parameters using test pumping software. Therefore the present study will be the first to estimate aquifer parameters. The approach taken with test pumping was guided by unreliable borehole yield, to this effect boreholes were not stressed via a multi-rate step test. Only constant discharge tests were conducted.

2.4 RAINFALL

The area forms part of the Namib Desert, thus the annual rainfall received in the study area is low. The average annual rainfall area is estimated to range from 100 mm/a to 200 mm/a (Figure 2-5). In other parts of the desert, rainfall is only around 15 mm per year, annual rainfall of greater than 100 mm have only been recorded in 1934, 1976 and 1978 (Boyer et al, 2000). In the central Namib Desert the mean pan evaporation rate of 3168 mm per year has been recorded with yearly values reaching 4000 mm, some as much as 200 times the mean annual rainfall (Jacobson & Jacobson, 2012).

Climatic features of Namibia result from its global location. The country is positioned between the latitudes 17 and 29 degrees south of the equator, where it is exposed to three major climate systems, namely; Inter-Tropical Convergence Zone (ITCZ) that controls rainfall patterns in inter tropical Africa, especially on the eastern sea board, Temperate High Pressure Zone and Temperate Zone, these systems' relative position affects rainfall patterns across Namibia (Mendelsohn et al, 2002). Inter-Tropical Convergence Zone feeds moist air from the north while the Sub-Tropical High Pressure Zone pushes moist air back with dry cold air, because the Sub-Tropical High Pressure Zone is most dominant, dry conditions prevail in most parts of Namibia

(Mendelsohn et al, 2002). As Mendelsohn et al, (2002) elaborate; the high pressure zone descends heating and drying as it reaches lower levels, resulting in few clouds, intense radiation from the sun and high day time temperatures.

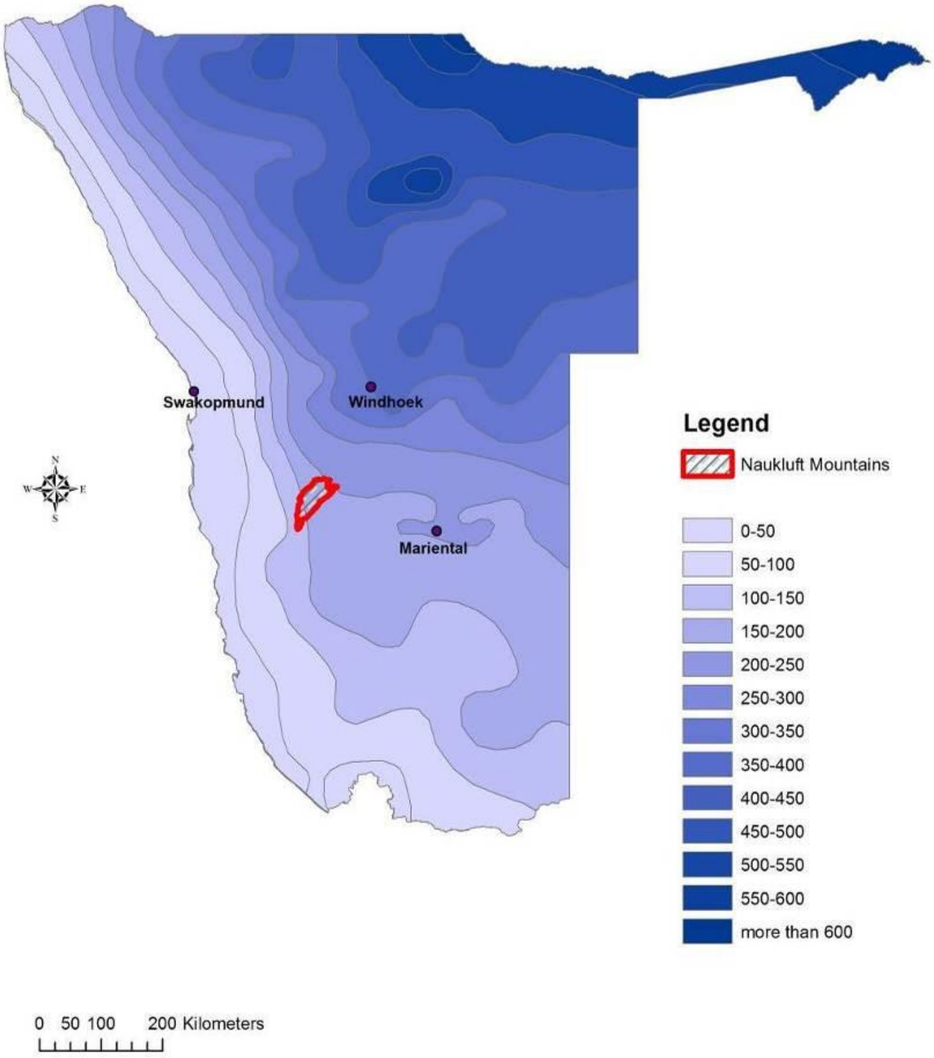


Figure 2-5: Average Annual Rainfall Distribution (After: Acacia Project, 2002)

Due to the nature of climatic elements variability is often observed in semi-arid and arid regions where rainfall variability is common as it has been observed in Ethiopia (Tilahun, 2006), Iran (Modarres & da Silver, 2007) and Botswana (Batisani & Yamal, 2010). Variability is both spatial and temporal (Tilahun, 2006, Batisani & Yarnal, 2010). Variability in rainfall may provide a general gauge regarding changes in natural behavior, a key step in the process is the ability to reveal change/s or trends present in rainfall records (Modarres & da Silva, 2007). This in turn is dependent on the availability of long-term data records and in the absence of these, trends cannot be established. Cloud bursts characterized by high intensity, high rainfall and short duration periods are prevalent. In Namibia, this triggers surface stream flows in ephemeral rivers and flash floods. This is in light of the fact that arid regions are characterized by very low mean annual rainfall (Zaman et al, 2012). This is further compounded by the fact that floods in arid regions are generally caused by storms of high intensity over a small part of the catchment. Rainfall is thus never fully distributed over large areas.

The challenge with understanding the hydrogeological system of the Naukluft Mountains is posed by data availability. Currently data is either limited in record period, lacking or if available it is not kept in a central place for easy access. In the case of rainfall data, there exists at various farms and homesteads data recorded from private rain gauges, which is available but is not consolidated and is often stored in hard copy format. Stream flow and evaporation data are extremely limited. Regardless of the foregoing, rainfall losses to surface flow and run off are observed though not quantified with confidence. Zaman et al (2012) reports high variability water losses are synonymous in arid regions mostly to run off and stream flow and losses to alluvial aquifers. Field observation during the rainy season of 2009 proved that during a cloud bursts, vast amounts of water are discharged from the Naukluft Mountains in the form of run off and flush flood as well as increased spring flow. It therefore alludes to the view that water losses from the Naukluft Karst Aquifer are high during the rainy season as well and less attributed to evapotranspiration supporting Raymond (2010)'s conclusions.

Naude (2010) in her stable isotope study of the hydrological systems in the Naukluft Mountains has investigated the isotopic content of rainfall from samples collected in the study area. Naude (2010) shows that samples collected in March 2008 plotted on the evaporation trend while, those collected in February 2009 plotted on the global meteoric line (Figure 2-6). Further an average $\delta^{18}O$ for all the precipitation samples collected precipitation samples during the wet seasons of 2008 and 2009 was -2.2 per mil, with an anomalous sample showed negative $\delta^{18}O$ value of -14.5 per mil and δD value of -95 per mil during a torrential rainstorm and was the most northerly rain sample collected. This is evidence that altitude and elevation had a more significant impact on isotopic concentration than rainfall content.

Cloud burst are generally correlated with temperature, the higher the temperature during the event, the heavier and more negative the isotopic content (Andreo et al., 2004), this would imply that high rainfall during cooler hours has lighter and less negative isotopic content higher temperature depletes lighter isotopes whilst cooler temperatures increases their concentration as they require less energy to condense. The northern end of the Naukluft Mountains is the most elevated and is at a lower latitude in comparison to the rest of the study area, the signature in the rainfall sample is proof to support the effects of the following factors on isotopic content in rainfall in the study area, factors correlated with temperature according to Andreo et al. (2004):

- When atmospheric moisture is low, the concentration of ^{18}O and ^{2}H will be higher in the vapor phase;

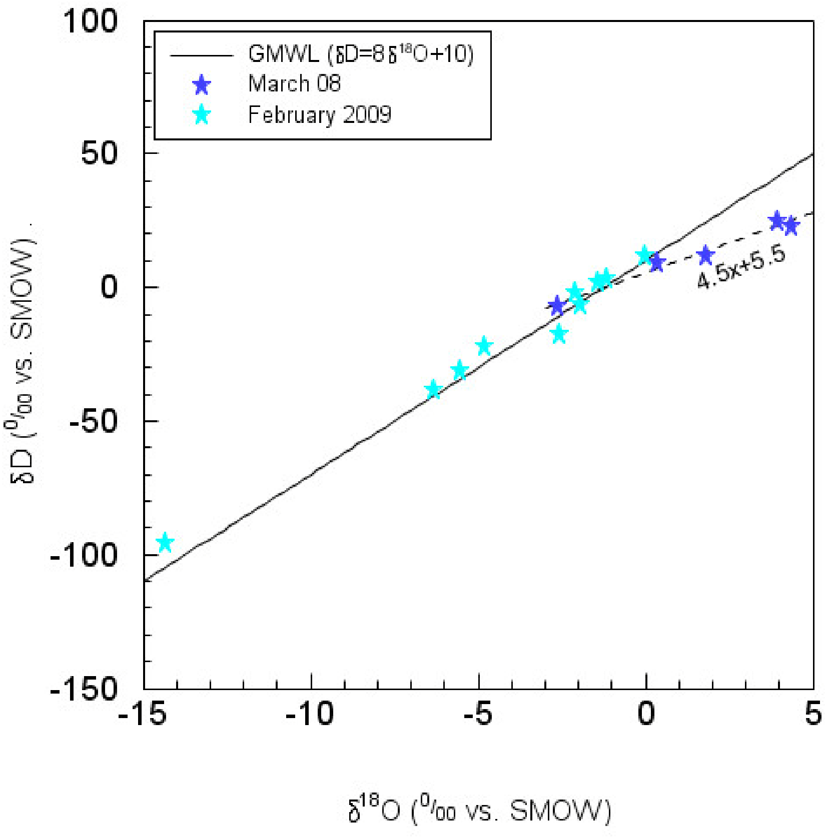


Figure 2-6: δ18O vs. δD for all Precipitation Samples. March 2008 Data Falls on an Evaporation Trend with an Equation δD=4.5δ18O+5.5. February 2009 data lies along the GMWL (After: Naude, 2010)

- Whereas with rainfall quantity; the higher the rain value the lower the heavy isotope content (this could be as a result of the energy required for condensation being less from vapor to liquid);
- Whilst with latitude; the lower the latitude the lower the heavy isotopic content, the same is for elevation;
- Continental effect; the greater the distance from the sea the lower the isotopic content; and
- Seasonal effect; summer rainfall have higher heavy isotopes than winter rainfall.

2.5 GROUNDWATER RECHARGE

Xu & Beekman (2003) define groundwater recharge as an addition of water to a groundwater reservoir. Recharge can be direct or indirect and it is dependent on various factors that could be related such as geological, soil texture and the nature of aquifers. It can be direct through direct infiltration of precipitation and subsequent percolation throughout the unsaturated zone into the aquifer (Xu & Beekman, 2003). Lerner et al (1990), further defines direct recharge as water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone till it reaches the water table. While indirect recharge results from percolation to the water table following surface run-off and localization in joints, as ponding in low lying areas and lakes through beds of surface water courses. Recharge can be further differentiated into recharge associated with surface water bodies and localized recharge resulting from horizontal surface concentration of water in the absence of well-defined channels.

The amount of water available for recharge at a given time is not only attributed to the amount of rainfall received but also to losses through evapotranspiration, base flow, interflow and abstraction. Natural recharge is controlled by climate, topography, geology, vegetation and land use changes. Recharge in Namibia is classed as episodic recharge which is driven by high rainfall events (Figure 2-7).

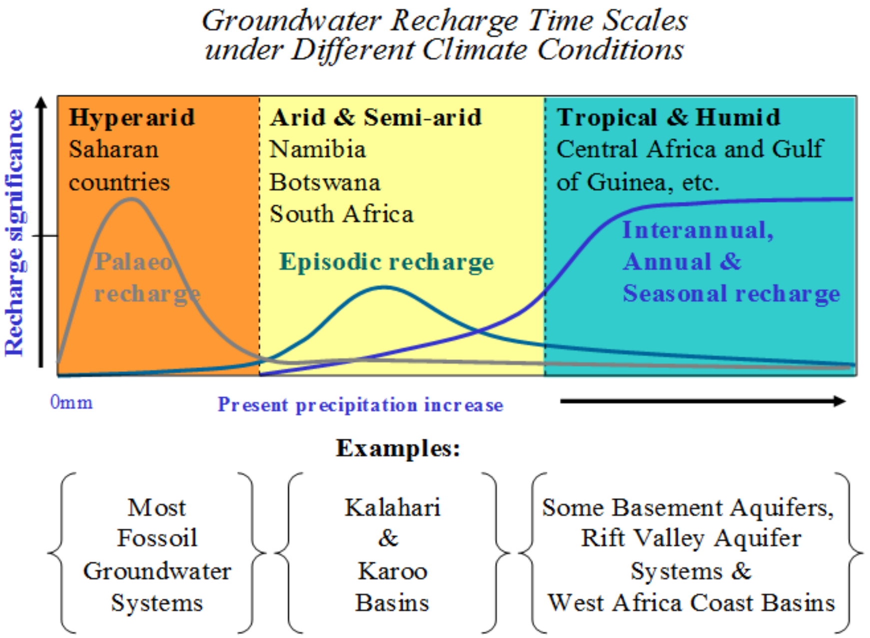


Figure 2-7: Classification of Recharge under Different Conditions, Arid and Semi-arid Regions Mainly has episodic recharge (After: Xu & Braune, 2010).

Various methods are used to estimate and quantify groundwater recharge. The Chloride Mass Balance (CMB) Method is one such method and it integrates fine and aerial distribution of groundwater recharge. This is so because the method integrates recharge in time and space and it appears to be well suited for areas with large temporal and spatial variation in recharge (Bazuhair & Wood, 1996). An application of this method assumes that:

- There is no chloride in the groundwater other than from precipitation;
- That chloride is conserved in the system;
- That steady state conditions are maintained with respect with respect to long-term precipitation and chloride concentration in that precipitation;
- Precipitation is evaporated and/or recharged to groundwater with no surface runoff leaving the aquifer area;

- No recycling of chloride occurs within the basin; and
- No evaporation of groundwater occurs up gradient from the sampling points (Bazuhair & Wood, 1996).

Guan et al (2010) indicate that chloride is the most commonly used environmental tracer for studying water flow and solute transport in surface water bodies. Further stating that the main source of atmospheric chloride is the ocean. Deposition of chloride in an unconfined permeable system can be either by wet or dry deposition. Guan et al (2010) describes, that chloride bearing aerosols can settle down to the surface by gravitational forces, it is highly dependent on wind conditions and aerosol size (dry deposition). Chloride bearing aerosols can be rained out; this process depends on precipitation characteristics. The sum of wet and dry deposition is important for hydrological applications as they give total chloride input.

Allison and Hughes (1983) showed that it was possible to estimate recharge from Cl profiles in the unsaturated zone, and this mass balance technique has been extended to the saturated zone, where it has been used successfully to estimate recharge in arid areas.

Huston (2007) and Shard et al (2006) apply the CMB Method estimating recharge in arid environments. In recharge estimations isotopes are often used together with CMB. In the case of application in arid and semi-arid zones where available water resources are often limited to groundwater, environmental isotope technique offers a powerful tool (Kattan, 1997). Praamsma et al (2009), Herczeg et al (1997) and Barbieri et al (2005) have all applied isotope technique in their respective studies to estimate recharge or map recharge areas in aquifers.

In Namibia CMB method has been applied to estimate groundwater recharge especially in the porous Kalahari Aquifer mostly confined to the north and northeastern part of Namibia combined with physical hydrogeological methods and relevant software. The aquifer is mainly defined by layers of Kalahari Sequence sediments of sand, sandstone, clay, calcrete and silcrete layers.

Külls (2000) estimated recharge and quantified flow systems in the Goblenz area in the northwestern Kalahari. His work was aimed at developing a conceptual model for groundwater recharge, describing mechanisms, their timing and regional distribution of the Kalahari aquifer. In addition the study aimed to develop a quantitative model of groundwater flows that contribute to the Kalahari aquifer at Goblenz as well as to assess the role of transmission losses from the Omabonde tributary and Omatako wash. CMB was used to estimate recharge.

Klock (2001) applied CMB Method when investigating the hydrogeology of the Kalahari in north-eastern Namibia with a special emphasis on groundwater recharge, flow modeling and hydrochemistry. The aim was to understand groundwater dynamics in the Kalahari catchment of north-east Namibia with respect to recharge and discharge areas and related processes. Recharge estimation involved filtration tests in the unsaturated zone of the aquifer, evaluation of rainfall data, pan evaporation, hydrograph interpretation and soil water balance. Klock (2001) estimates that the most of the groundwater divide in the study area receives recharge amounts between 1 and 50 mm/a. Further, groundwater recharge of 10 mm/a was approximated for areas where quartzite of the Nossib Group out cropped. Klock (2001) showed that calcrete and Kalahari sand thick cover reduced localized recharge in joints and fractures as recharge is limited to 1 mm/a. If joints in the quartzite are closed by calcrete, or where a thick cover of sand occurs, the recharge rate is limited to less than 1 mm/a.

Külls (2000) reports on the work done by Mainardy in 1999 in fractured aquifers in the Waterberg area, where local recharge was estimated using CMB and fracture aperture measurements in outcrops of sandstone, dolomite and marble with small moderate slopes found to provide favourable recharge conditions. In this study recharge rates of 16 to 24 mm/a were determined for fractured sandstone in the western part of Waterberg, much lower recharge rates of 1 to 8 mm/a were estimated for quartzite outcrops of the Nossib Group and meta sediments of the Damara Sequence.

Bäumle (2003) with the model developed in his investigation of the Tsumeb karst aquifer showed that direct recharge within the area of carbonate outcrops amounts to 4% of the mean annual rainfall or 21 mm/a which was interpreted to be 12 times higher than the direct recharge in the Kalahari foreland.

In their work within the Nauklfut Mountain area Turner (2008), Bernhard (2009) and Raymond (2010) have shown the significance of the mountains pertaining to recharge in the area. General flow of groundwater has been established by Christelis and Struckmeier (2001) and Turner (2008).

2.6 GROUNDWATER MODELLING

Groundwater modeling may be defined as a simplified version of a real-world system that approximately simulates the relevant excitation-response relationship of the real world system (Bear et al, 1992). J. Toth in 1963 used for the first time analytical solutions to investigate groundwater flow in hypothetical; small drainage basins (Zhou & Li, 2011) and over time groundwater modeling has been driven by the demand to predict regional impacts of human inferences on groundwater systems and surrounding environments (Zhou & Li, 2011). In this regard, the use of models in hydrogeology has become a fundamental part of solving groundwater system issues that span from recharge to contamination. Biesheuvel and Hemker, (1993) agrees by adding that groundwater modeling is an important tool in acquiring knowledge about quality and quantity of groundwater and groundwater flow systems. Nowadays groundwater models are used as:

- Interpretative tools investigating groundwater dynamics and flow;
- Simulation tools for analyzing responses of the system to stress;
- Assessment tool for recharge, discharge, storage and quantification of sustainable yield' and
- Support tool for planning, and so forth (Zhou & Li, 2011).

It is common to conjunctively apply modeling with other tools such as Digital Elevation Models (DEM) and related spatial data in a Geographical Information System (GIS) environment. Elevation data sourced from satellites like ASTER and SRTM amongst others provide an information in terms of topographic orientation, identification of drainage systems to name a few. Ludwig and Schneider (2006) in their study validated the uses of SRTM data in hydrogeological models, looking at errors that may be associated with such data. The application of GIS in modeling allows for the processing of large sets of data on hydrogeological frameworks, hydraulic parameters, hydraulic stress and measured heads (Zhou & Li, 2011) as well as land use and vegetation.

Fleury et al (2007) applies rainfall-discharge model to a karst aquifer in the south of France simulating discharge for a period of ten years. Kazhaei et al (2003) applied a groundwater model whose main purpose was to assess groundwater recharge to aquifers taking into account main recharge mechanisms including sub-surface flow in the alluvium and recharge from beds of ephemeral rivers, based on the concept of routing precipitation within and through the catchment.

Peck (2010) simulates groundwater flow in her study of the Stampriet Artesian Basin in southeast Namibia. The study aimed to increase the understanding of the system in the recharge member state and assist in the multi-lateral management of the aquifer system by using an interactive ‘what-if’ scenario model of the Auob Aquifer, which allows the user to modify inputs and outputs in order to predict quantity estimates within the system.

Winker (2010) developed a groundwater model for the Swakop River Basin, with the objective of developing an initial understanding of the groundwater flow. This was achieved by a numerical model using Groundwater Vistas which couples a model design system with a graphical analysis tool as well as the flow and transport model of MODFLOWSURFACT. Three models were developed by combining different recharge-, evaporation-, and aquifer concepts taking recharge at a minimum of 0.5% and maximum of 1% of annual rainfall.

2.7 GROUNDWATER STUDIES FOCUSED ON THE NAUKLUFT MOUNTAINS

Turner (2008) looked at the geochemical analysis of ground and surface water in the Naukluft Mountain area. Through his work, two groundwater flow regimes from the Naukluft Mountains, both generally flowing to the west to the Tsondab and Soussisvlei were identified. The study established that the Naukluft Mountains had a low Total Dissolved Solids (TDS), salinity and Electrical Conductivity (EC) values whereas the surrounding areas had higher corresponding values especially to west of the mountains to the Namib Sand Sea. The Naukluft Mountains are main recharge area as well as high discharge area in this region (study area), and that there is little seasonal variation in groundwater quality in the northwestern part of the study area compared to the southwestern part. Turner (2008) further showed that the two main rivers in the study namely the Tsondab and the Tsauchab have distinct water chemistry.

Bernhard (2009) researched mean residence time of groundwater in the Naukluft Mountains, looking at elevation on carbon isotopes as well as sustainable management of water. Water samples were collected from different sites in the study area and analyzed. The results showed that:

- The Naukluft Mountains are the main source for the recharge of groundwater both in the alluvial aquifers and the crystalline aquifers;
- Groundwater gets older towards the west of the mountains, which Bernhard (2009) related to the geomorphology of the mountains; and
- The water can be grouped into four categories, namely modern waters, waters aged 100's of years, water aged several thousand years and lastly water aged much older than several thousand years. Ranging from 23 to 15543 thousand years aging from the north to the southwest of the study area.

The groundwater in the Naukluft region is confined to carbonate aquifers of the Damara and Nama groups (Bernhard, 2009) as well as alluvial aquifers that have formed around the mountains following the drainage of the two rivers and their tributaries.

Raymond (2010) studied nitrates and sulphate isotopes in surface and groundwater from the mountains. The study was motivated by high levels of nitrate in the area bearing in mind that high nitrate values are sometimes found in arid and semi-arid regions where population density is low and agriculture and livestock is non-existent. Raymond (2010) concluded that:

- Water levels are often shallow and has a high response to seasonal change and is directly influenced by local drainage basin around the boreholes, therefore aquifers are vulnerable to contamination;
- Recharge is localized and rapid and geological substrates have a high influence on water hydrochemistry;
- Evaporation is ruled out as a reason for high ionic concentration but is attributed to high temperatures in water rock interactions and contamination from animals through preferential path ways near watering points; and
- Elevated sulphate concentration is linked to gypsum dissolution into the groundwater.

Naude (2010) conducted a detailed stable isotope study (δ^{18} O, δD and δ^{13} C) of precipitation and groundwater there by providing numerous possibilities of recharge and aquifer characterization. The three objectives of Naude's (2010) study were to determine the recharge processes in the Naukluft Mountains by studying the relationship between the groundwater and precipitation, determine recharge per year by looking at the shift of δD between groundwater and precipitation as well as determining the frequency in recharge by looking at seasonal variation and radiometric isotopes. The study showed that the river, stream and groundwater have average δ^{18} O and δD values ranging between -7.0 per mil and -5 per mil and -45 per mil and -30 per mil respectively, plotting close to the Global Meteoric Water line. Large variability between groundwater and precipitation for stable isotope values implies that only large rainfall events infiltrate the Naukluft Aquifer (Naude, 2010). Samples analyzed from boreholes showed distinct spatial differences and the plotted spatial distribution of stable isotopes indicate that boreholes tap from two distinct aquifers (Naude 2010). Overall the δ^{18}O isotope values from all sources for all sampling seasons range between 8.0 per mil and -4 per mil and the δD between 25 per mil and -

95 per mil. Stable isotopes of surface and groundwater vary spatially with latitude, altitude and seasonality while those of precipitation varies with the amount of rainfall. $\delta^{18}O$ and δD values of borehole samples did not change significantly over the sampling season with a standard deviation of 0.18 per mil and 2.18 per mil for $\delta^{18}O$ and δD respectively. This could mean that groundwater has either an isolated source unaffected by local precipitation and river water or it is a large body of well mixed water that is able to homogenize the less negative precipitation isotope values. Naude (2010) could not deduce for certain if precipitation during the sampling season was responsible for aquifer recharge. This could have been observed if there were monitoring boreholes in the area that would record the responses of the aquifer to that particular rainfall event. The rain season samples do not all exhibit high negative isotope values as expected; this is only observed in spring samples, which Naude (2010) interprets to mean that local recharge occurs in certain parts of the study area.

Through the study it was shown that $\delta^{13}C$ is more inorganic carbonate than organic, Bernhard (2009) revealed that carbonate dissolution has more of an influence to the composition of $\delta^{13}C$ in the groundwater. The comparisons with other karst aquifers by Naude (2010) indicate that the Naukluft waters seem to be more homogenous. This comparison seems to indicate that climate indirectly affects the $\delta^{13}C$ values and also that drier climates have values closer to 0 per mil. This could also be interpreted to mean that the carbonate aquifers have a greater imprint on the isotopic composition of the water.

Naude (2010) characterizes Naukluft waters in relation to recharge process in the aquifer, looking at the behavior of isotopes in rainfall, groundwater and surface water; it was observed that groundwater and surface water have more negative δD and $\delta^{18}O$ values compared to the precipitation in the Naukluft.

Naude (2010) further explores various possibilities as to why the groundwater in the Naukluft is more negative (depleted of heavy isotopes) than the local precipitation; firstly in semi-arid regions, only large storm events recharge groundwater systems. Secondly, that the groundwater has migrated kilometers from higher elevation and higher latitude and accordingly can have lower δD and $\delta^{18}O$ values than the local precipitation. Lastly, this discrepancy may be explained by the groundwater being recharged during ancient pluvial periods when meteoric precipitation had different values and a lower deuterium excess than today.

The results from Naude's (2010) work indicate that surface water contains a significant groundwater signature indicative of 'pre-event' water. The average $\delta^{18}O$ and δD values of surface water in the Naukluft are -5.3 per mil and -35 per mil respectively. These values are significantly closer to the groundwater $\delta^{18}O$ values ($\delta^{18}O = -6.7$ per mil and $\delta D = -44$ per mil) than that of precipitation ($\delta^{18}O = -2.2$ per mil and $\delta D = -9$ per mil). However, the Tsondab River with no spring supplementing it, has more negative $\delta^{18}O$ and δD values than rain water but less negative values than the other surface waters. This according to Naude (2010) clearly indicates a mix between pre-event and event water. Naude (2010) deduced that evaporation is not a major process during wet years as results do not show change in isotopic composition and that they fall on the Global or local Meteoric Water line. However, evaporation occurs in the dry years as indicated from the 2008 samples.

Buffat (2012) in her study on nitrate isotopes aimed to provide supplementary information and an emphasis on long-term changes of the same sample locality as those from Raymond's (2010) study. Therefore, Buffat (2012) continued the work started by Raymond (2010) seeking to better understand nitrate contamination in the Naukluft Mountains. Buffat (2012) for the first time investigated plants as a starting point for $\delta^{15}N$ and $\delta^{18}O$ because soil composition is reflected in the plant composition of ammonium and nitrate. Quoting Naude (2010) and Carol Morel (work in progress), Buffat (2012) indicates that 2009 and 2011 are interpreted as recharge years for the Naukluft as precipitation measured during these years does not fall on the Global Meteoric Line. In her results Buffat (2012) observed the spatially complex distribution of nitrate values. High concentrations of more than 100 mg/l are attributed to anthropogenic activities (livestock farming and sewage waste), while those that are lower are due to biological fixation near the surface and denitrification occurring in the unsaturated zone. Nitrate concentration in water samples varied from 6.6 to 552.9 mg/l with a mean concentration of 102.9 mg/l. $\delta^{15}N$ values ranged between +2.4 and +18 per mil while $\delta^{18}O$ ranged between +1.6 and +16.2 per mil. Buffat (2012) states that non evaporatic line observed for δD and $\delta^{18}O$ values indicate that infiltration rate of precipitation is likely to be rapid, further observing that aquifers are recharged during the rainy season and only by sufficient rainfall. The hydraulic system is likely to be closed since most samples do not show seasonal variation. Aquifers that show seasonal variations are likely to be recharged more recently (Buffat, 2012). Two aquifer systems are defined by concurring with Turner (2008) and Naude (2010), namely the Tsondab and Tsauchab basins. Naude (2010) had observed different isotope signatures for the rivers. Buffat (2012) supports Turner (2008) on two westerly groundwater flow regimes that are defined by the two rivers; the author further alludes to a more uncertain flow regime towards the east.

CHAPTER 3: PROJECT RATIONALE

This section outlines the objectives of the study, the rationale and study limitations

3.1 OBJECTIVES OF THE STUDY

There are four main objectives for the study:

- To give a summary of the geology and a detailed lithostratigraphy of the study area.
- To classify and name aquifers, determine aquifer parameters of the aquifers that are in the study area;
- To estimate rainfall available for groundwater recharge and define the role that the Naukluft Mountains plays in groundwater recharge in the area;
- To investigate groundwater flow and the influence of the mountains on groundwater flow in the region surrounding the mountains; and

Major components of the study are addressed through:

- Utilizing geological information available;
- Bringing together previous studies that form part of the wider Naukluft project to define the hydrogeological character of the study area;
- Incorporating a hydro-chemical classification to identify in-and outflow areas between the NNC and adjacent aquifers;
- Deriving groundwater aquifer parameters from a number a hydraulic tests;
- Estimating rainfall available for groundwater recharge from rainfall data using the CMB method; and

- Manipulate Digital Elevation Model data through Arc-GIS 10 software to have a 2-D view of the study area to highlight the implication for groundwater flow based on orientation and propose a conceptual groundwater model.

3.2 PROBLEM STATEMENT

The Naukluft Karst Aquifer has in recent times received attention from other scholars in the field of hydrogeology, a welcome change as most of the focus had been on its spectacular geology. This could be due to the following reasons;

- **Location in relation to the aquifer's relevance as a strategic aquifer**: Because of its sparse population groundwater use has been only for local consumption. Although the Naukluft Karst Aquifer is strategic, the cost of developing its resources to its full potential is very high. The national focus has been on areas with high population and those with conflicting users as well as those that have a low cost development ratio;
- **Classification as part of a national park**: Because the aquifer is part of the Namib-Naukluft Park where the desert environment is protected and preserved, focus has also been on environmental aspects and the area's touristic potential;
- **Geologic spectacle**: Because of the interesting geology the focus has been more biased towards understanding its geomorphology and structure first then its hydrogeological systems second; and
- **Financial resources for research**: Most research on water in the Namibia is driven by government finance and priority is given to developing aquifers with a high density of the population or where conflicting users are present. Limited resources have hindered work

on the Naukluft and in this regard most of the recent studies done including this one are academic theses which are part of a wide project.

Previous studies in the Naukluft Mountain area laid the foundation for future work in terms of aquifer research, aquifer development and utilization especially demand on resources with increasing population and economic growth. This study seeks to add and also to draw from the foundations set.

The Naukluft Karts Aquifer is strategic in terms of the Tsondab-Koichab Basin and in that scope it is an advantage if more questions are raised and solutions are sought on the aquifer.

Turner (2008), Bernhard (2009), Raymond (2010) and Naude (2010) and others as stated above have investigated aspects of hydrochemistry and through their work they have shown the character of the waters in the Naukluft system. In their work, the role of the Naukluft Mountains in terms of recharge has been established. Bernhard (2009) and Naude (2010) have looked at recharge by looking at the residence time in relation to the carbon cycle and stable isotopes of ^{18}O, ^{13}C and ^{3}H respectively. Whereas Mangeya et al. (2008) has estimated recharge for a small area of the mountains.

In view of the bigger picture, the work done on the hydrology of the aquifer are a small fraction of what can be studied, compared to the magnitude of work done on the Otavi Mountain Karst Aquifer where the work of Bäumle (2003) as part of the DWAF project which resulted in quantification and classification of resources in that aquifer, control of groundwater abstraction via a permit system and formation of a groundwater management body. The aquifer is now used as a basis for groundwater management amongst different user groups.

Naukluft Karst Aquifer does not compare to the Otavi Aquifer due to lack of data collection and vital research infrastructure, thus validation of results is not based on long-term data. Knowledge gaps into the hydrogeologic characteristics of the aquifers in the study area and how they are related or differ in relation to groundwater flow as well as the relationship between the different aquifers still exist.

The Naukluft Mountains are the main recharge and discharge area in the region as the mountains receive more rainfall than any place in the Namib Desert (Bernhard, 2009; Turner, 2008 and Raymond, 2010); this benefits surrounding aquifers more than the Naukluft Karst Aquifer as high surface discharge from the mountain area during rainfall lowers groundwater recharge. The hydrogeological potential of the Naukluft Mountains from the work of Christelis and Struckmeier (2001) clearly indicated their strategic importance to the hydrogeologic regime in this part of the Namib Desert. However, there is a need to look at a local perspective of groundwater flow and aquifer characteristics which is expected to enhance further the significance of the mountains to the regional groundwater system. In recent times hydrochemistry studies looking at cations, anions, nitrates and isotope have shed some light on the situation in the area.

Although Recent studies (Turner, 2008; Bernhard, 2009 & Raymond, 2010) have looked at hydrochemistry and have further attested to the importance of the Naukluft Mountains in relation to recharge and discharge, aquifer properties, groundwater flow regime, recharge estimation especially in terms of how the mountain aquifer influences surrounding aquifers, the role that the Naukluft Mountains play in the hydrogeological system as well as the an estimation of a water balance is still poorly understood.

Anecdotal evidence from a number of the farmers in the Naukluft Mountains points to changes in the hydrogeological regime, manifested principally in the drying up of a number of natural springs (Mangeya et al, 2008). This phenomenon most likely represents fundamental changes in the hydrological regime brought about by man-made activities in the region. For these reasons, a hydrogeological investigation of the Naukluft Mountains is undertaken to investigate the nature of its hydrological regime and to offer estimates of the groundwater recharge and the implications for water supply in the region.

3.3 STUDY LIMITATIONS

The limitations of this study are outline and discussed below:

- **Data availability**: data collected in the study area as part of the wider Naukluft project is very limited. This was a result of funding constraints;
- **Reliable and complete borehole lithology logs**: lithological logs for pump tested boreholes during this study were not found; implying that subsurface geology was inferred therefore determining the lithology intercepted by these boreholes was based on the orientation of the geology. Borehole depth as well as aquifer thickness was not accurately known. Further initial yields of the boreholes are unreliable. Limits in initial yield information means that full test pumping procedures could not be followed; in this case multi-rate step tests could not be conducted, instead they were pumped at a capacity that could allow the longest possible test period.
- **Limited long term and well distributed rainfall data**: one long term data set was found, dating from 1950 to 2006. This has resulted in approximation and extrapolation of rainfall data in order to have a rainfall representation for the Naukluft Mountains.

- **The lack of a groundwater monitoring network**: there is no long term water level data in the study area, indicating a lack of historical data which would show how the water table in the region responded to weather events and abstraction. Therefore there is no comparison component between groundwater levels and rainfall in this study. Most of the boreholes are installed with windmills, thereby making it almost impossible to take water level measurements as well test pump. Thus only accessible boreholes were pump tested.
- **Limitations in developing a conceptual flow model**: due to lack of standard borehole reference points which could have been used to accurately estimate actual groundwater levels as a result no water level contours are included in the conceptual model.
- **Limitation in availability of surface water data**: River runoff data was not available due to system failure in the database software. Therefore was no quantified runoff data from the station in the Tsauchab River at Sesriem.

CHAPTER 4: METHODOLOGY

4.1 RESEARCH DESIGN

This study relies on the analysis and evaluation from studies that have tapped into the hydrochemistry database developed since the wider Naukluft Project led by Prof. B. Mapani and Dr Jodie Miller commenced in 2008. This study can therefore be viewed as an amalgamation of different studies conducted with a major aim of understanding the NNC aquifers and the associated Tsauchab and Tsondab aquifers. Further this study fills in the gap of understanding the hydrological flow, recharge estimation and estimation of hydraulic parameters. An attempt is made to establish baseline estimate figures using the wider project database.

4.2 PROCEDURE

In this section the methodologies utilized in this study are discussed. This will include elaboration of the field work carried out, water sample collection and analysis, aquifer characterization and recharge estimation, the approach adapted in developing a conceptual model and evaluation of test pumping data.

4.2.1 FIELD WORK

During the inception of the Naukluft Project in 2008, three field seasons were envisioned, these were extended to five field seasons (last being in June 2012). The first two seasons were aimed at determining the bulk information on the location of sampling points and initial status of the hydrochemistry of the area. The seasons that followed were undertaken to allow more detailed study on high interest areas. These trips were carried out in the months between March and October.

Although this study relies on prior studies it was necessary that one acquired the background on the whole project, hence the author of this current study was involved field work of the wider project. As such one was exposed to the different methodologies that student peers were employing in their work. This approach also provided good orientation to the study area. Field work was restricted to short water sampling programmes yet still allowed a good spread of spatial and temporary data to be collected. Existing boreholes, where accessible were the primary targets as well as natural springs (refer to Figure 1-1).

4.2.2 COLLECTION OF WATER SAMPLES

All sample bottles intended for dissolved inorganic carbon isotope analysis were acid washed with 1% HNO_3 and allowed to stand overnight. These bottles were then rinsed with de-ionised water and allowed to stand overnight before final rinsing with de-ionised water and drying. Water samples for oxygen and hydrogen isotope analysis were collected directly from the source and added straight to 25 ml glass bottles using a sterile 60 ml syringe. Boreholes were pumped (purging) before sample collection (Figure 4-1 a). Water samples for dissolved inorganic carbon analysis were filtered through 0.45 µm cellulose acetate filters into the acid washed 25 ml glass bottles (Figure 4-1 b). Bottles were filled so that no air was present and then sealed with tape and stored at ~4 ºC until analysis. Samples for cation and anion analysis were collected in blue-capped 50 ml polypropylene sterile bottles.

Figure 4-1: Sampling Around the Study Area.

(a) Taking onsite physical parameters; (b) Filtration of water samples; (c) Pumping out a borehole before sampling and (d) Sampling from a tank using a bailer.

Samples for both cation and anion analysis were filtered using a 0.45 µm cellulose acetate filter and then 1 ml of 65% HNO_3 was added to the sample for cation analysis. The anion samples were stored at ~4 ºC until analysis.

On site field parameters were analyzed utilizing probes; these are Temperature, pH, Dissolved Oxygen, Salinity, and TDS as well as dissolved oxygen (Figure 4-1 c). Sampling point access at times was a challenge (Figure 4-1 d).

For the isotopic nitrate, analyses between 6 and 12 mg of nitrate per sample are needed. The water samples were tested with a nitrate test-kit; (nitrate strips and nitrate tester via -

colorimetry) to estimate the NO_3^- concentration on-site. For example; for water sample containing 60 mg of nitrate per-litre (estimated by the nitrate test-kit), a 20 ml sample of water. Nitrate was then collected by passing the water through an anion exchange resin (Bio-Rad AG1-X8, 200-400 mesh in the chloride form) with syringes equipped with 0.45 μm acetate-cellulose filters to retain particles that may block the resin. Nitrates have a relatively high affinity for the chloride ions and are thus concentrated onto the resin. An appropriate flow rate of 500 to 1000 ml/h through the column needs to be respected in order to get all of the nitrate contained in water. This technique of nitrate collection has two main advantages; first, the transport of the samples to the laboratory is easy as small sample vials concentrated with nitrate can be returned to the laboratory rather than samples of litres of water. Secondly, one can collect water with very low nitrate concentrations while nitrate is concentrated within the resin. The columns are then capped and stored in a fridge in order to avoid bacterial activity and potential nitrogen transformation. Sites for sampling plants were chosen to have a range of different representative species. The type of plant collected was noted and stored in plastic bags.

4.2.3 GEOCHEMICAL ANALYSIS

The first analysis started on site, when basic water parameters (pH, EC, DO and Temperature) are measured at the same time as the water samples are collected and computerized in the field to give immediate analysis of basic variation in water quality by using handheld probes that can instantly measure the parameters in the field. The second part of the analytical program involved sending water samples to Stellenbosch University for analysis of trace minerals. Tracer minerals including chloride as well as cations were analysed using Induced Coupled Plasma Mass Spectrometry (ICPMS) this is because this method is highly sensitive and has a capability of determining metals at concentrations below one part in 10^{12}. Isotopes (O, H and C) were analysed at the isotope laboratory in Cape Town, some isotope analysis was also conducted at the University of Luasane, Switzerland. These parameters yielded excellent information on the quality of the water present, the host rocks through which the water has travelled, and an indication of the residency time and the role of evaporation in recharge potential of the groundwater. Laboratory based analytical work closely followed the field sampling campaigns. As a result of the field work done, a database was developed and utilized as part of this study.

Data was computed into project database and utilized by all Naukluft project students

4.2.4 AQUIFER CHARACTERISTICS AND RECHARGE ESTIMATION

During the June 2009 sampling season (third sampling season), boreholes were identified and targeted for a reconnaissance test pumping by the author of this study, aimed at providing preliminary transmissivity and the storativity coefficient values for the aquifer system at different locations. These parameters have been calculated using the Cooper-Jacob time drawdown and Theis equations fitting formula curve solution in pump test analyses software. A submersible pump was used to pump the water for maximum 24 hours when the conditions allowed. As part of pump tests, digital data loggers, dip meters, GPS handheld modules and a stop watch were used to collect the data. The water was discharged into storage facilities of the owners of the boreholes. Computer based programs have been used to model the results. Arc-GIS 10 (Esri, 2010) has been used for this study to analyze groundwater level data to visualize borehole locations, sampling sites and groundwater flow. In particular, the hydromechanics of the region has been analyzed given the deformation that is preserved in the geology of the Naukluft Nappe Complex itself. This may be particularly important, as the carbonate rocks are likely to have little intrinsic porosity, such that fluid flow would be predominantly channeled in fracture networks (Ingebritsen et al., 2006). In addition, to these features the potential significance of composition in the sediments and the sands that dominate the Tsondab River valley has also been examined to determine the recharge potential of surface runoff. No tests were done in the Tchauchab River.

Analysis of results from the samples collected as well as interpretations from other studies has been utilized in recharge estimations using the CMB method. This method has been used extensively and is one of the suitable methods especially in arid to semi-arid regions such as the Naukluft Mountains (Xu and Beekman, 2003; Klock, 2001; Kül1s, 2000). Analysis of rainfall data is employed to provide a historical view of the weather patterns that are also indicative of major recharge events.

The study area is in relatively close proximity to the Atlantic Ocean, this indicates wet and dry deposition of chloride can be rather significant. However, for this study only rainfall samples were collected and analyzing for chloride concentrations (wet deposition), no samples were prepared to determine dry deposition. It is viewed that for the purpose of this study only wet deposition concentrations would be sufficient, taking into consideration the level of the study and the fact that no water balance is calculated for the study area. Therefore the estimates calculated for this study should be viewed as a lower limit.

The formula applied in estimating the recharge flux using Chloride Mass Balance is adapted from Bazuhair & Wood (1996):

$$Q= (p)\,(Cl_{wap})/\,(C_{lgw}) \qquad \textbf{Equation 4-1}$$

Where **q** = is the recharge flux, **p** = is average annual rainfall, **Cl_{wap}** = concentration of chloride in precipitation & **Cl_{gw}** = concentration of chloride in groundwater

Results are computed in Microsoft excel for each sampling points, where the average value of chloride concentration form the rainfall samples collected in 2008/2009 rainy season is used. Both the local average rainfall and national average rainfall figures are used.

4.2.5 *Conceptual Modelling Applying GIS and ASTER Global DEM Data*

A conceptual hydrogeological model of the study area is created using feature objects (points, arcs and polygons) and stored in a modelling system approach taken by Zhou & Li (2011). The modelling processes as outlined in requires various sources of data in a continuous system with feedback links as data collected is used to define the model, calibrate as well as update it continuously. The approach taken for the conceptual model in this study is very similar to Biesheuvel & Hemker, (1993), however due to the scale of the study area and the overall project, the conceptual model is more of an evolving framework that is based on limited data collected and visualized and manipulated in an Esri-Arc-GIS 10 (Esri, 2010) environment.

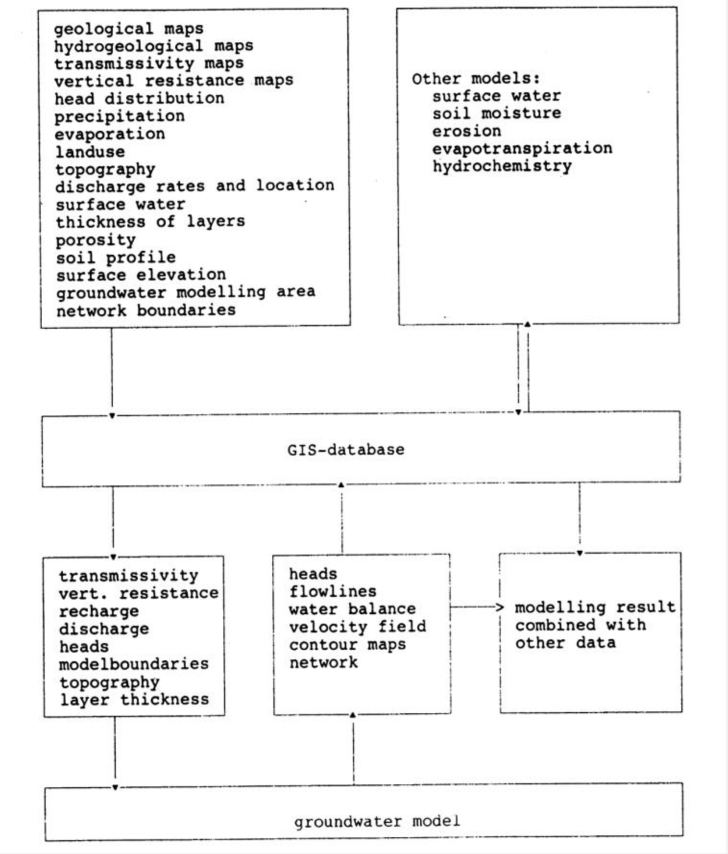


Figure 4-2: Conceptual Groundwater Modeling Framework (AfterBiesheuvel & Hemker, 1993)

Within the Arc-GIS 10 (Esri, 2010) environment, data files were created using point data with information such as longitude and latitude as well as location name amongst others, computed in Microsoft excel. The point data was collected within the area of this study. The point data files were imported into an Arc-GIS project set up to create shapefiles or layers that were then projected to show a spatial representation of the point data. At this stage manipulation of shapefiles yielded several maps used in this study. A simple schematic of layer visualized in Arc-GIS is shown in Figure 4-3, while the user interface of the Arc-GIS project used in this study is indicated in Figure 4-4 where the visualization of 90 meter by 90 meter resolution ASTER Global DEM data downloaded from the United States Geological Survey website in a format that allowed manipulation once imported in Arc-GIS 10 (Esri, 2010) was done.

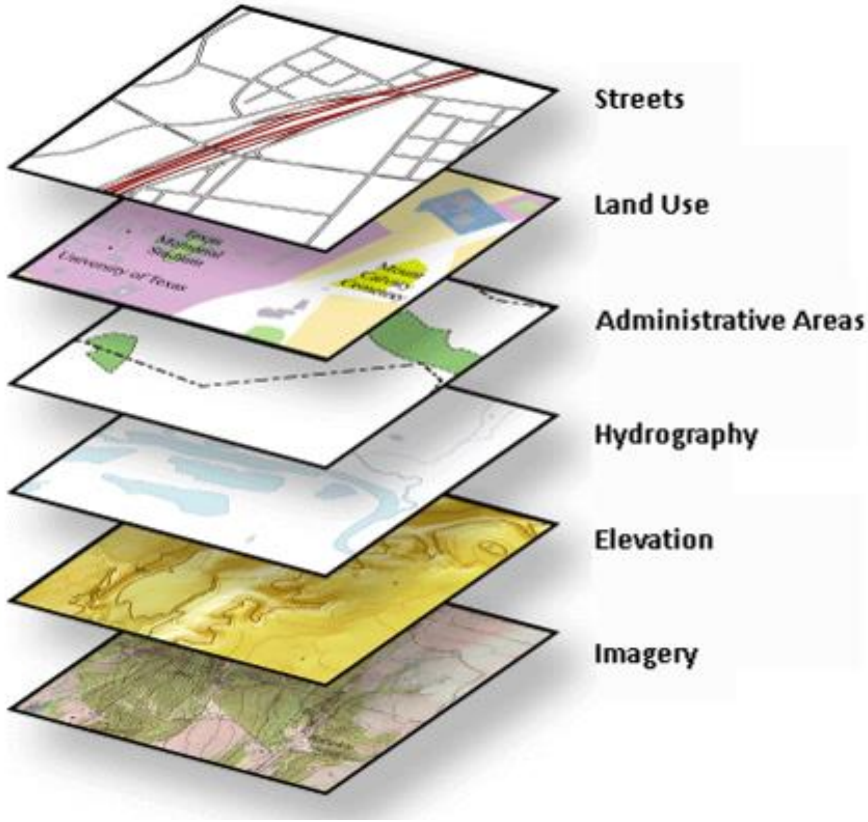


Figure 4-3: Schematic of Spatial Layers Overlain in a GIS Software

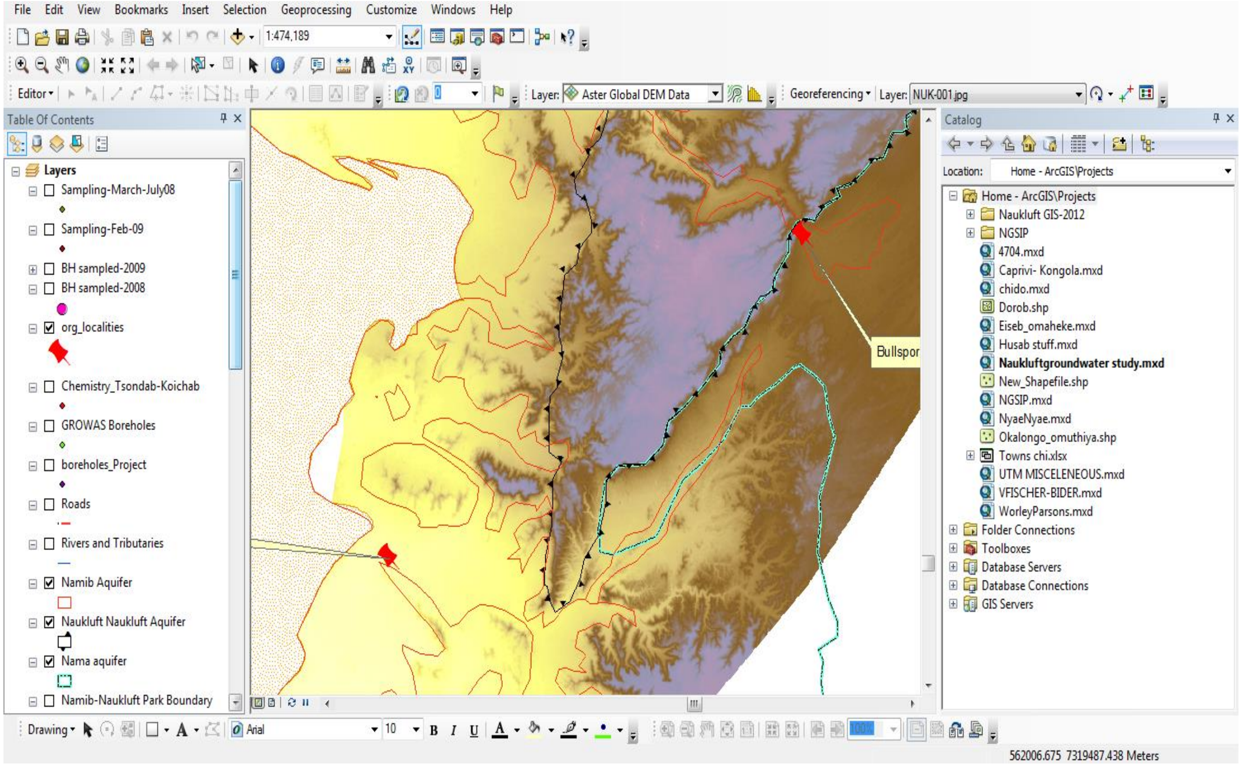
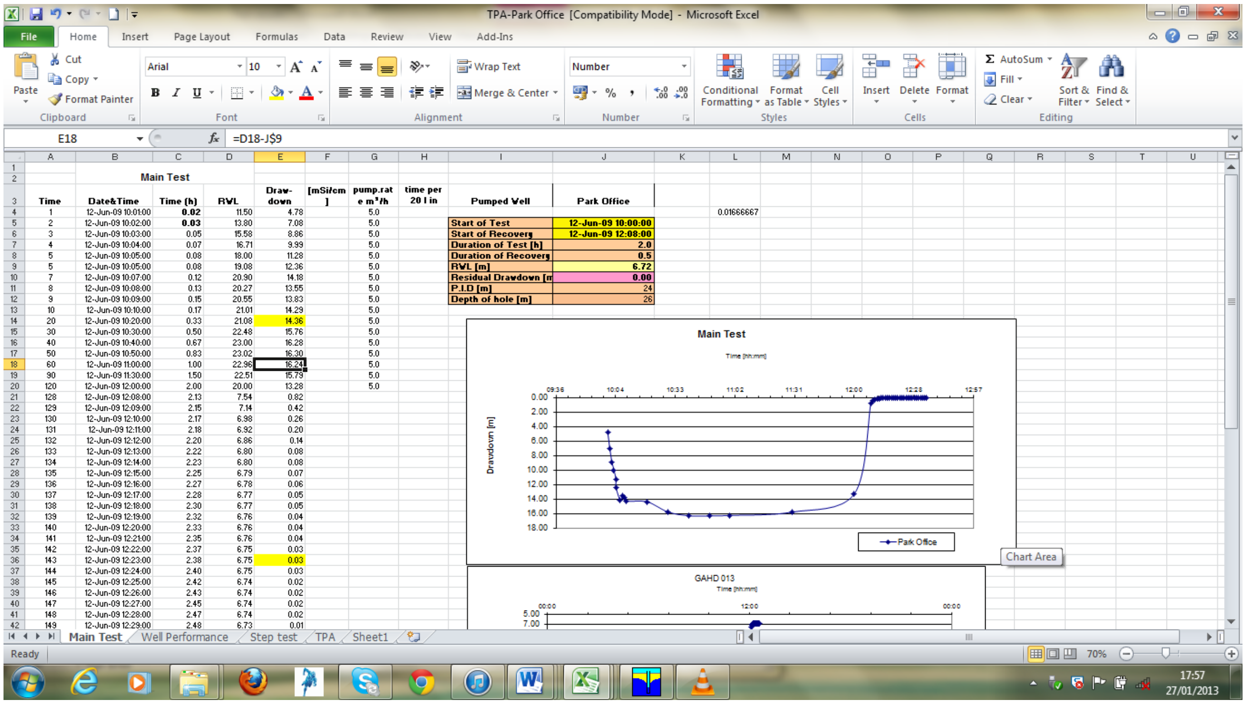


Figure 4-4: Desktop Esri-Arc-GIS Layer Schematic and Project Interface Used in this Study.

4.2.6 EVALUATION OF PUMPING TEST; TPA SOFTWARE APPLICATION

Test Pumping Analysis (TPA) software was developed by Ingo Bardenhagen in 2000, as a tool for analyzing pumping test data from fractured and non-fractured aquifers and is adapted for Namibian conditions. The first stage of applying the software is data preparation in an excel based spread sheet, as shown in Figure 4-5, before it is imported into the software where formula curves are fitted to calculate aquifer parameters (Figure 4-6). By Using the TPA software, uncertainties during preliminary evaluation of test pumping data done in this study limited and the parameters estimated have a lower margin of error. However other advanced pumping test software such as AquiferTest Pro are viewed more suitable for high level modeling and evaluation of test pumping which is accepted internationally.



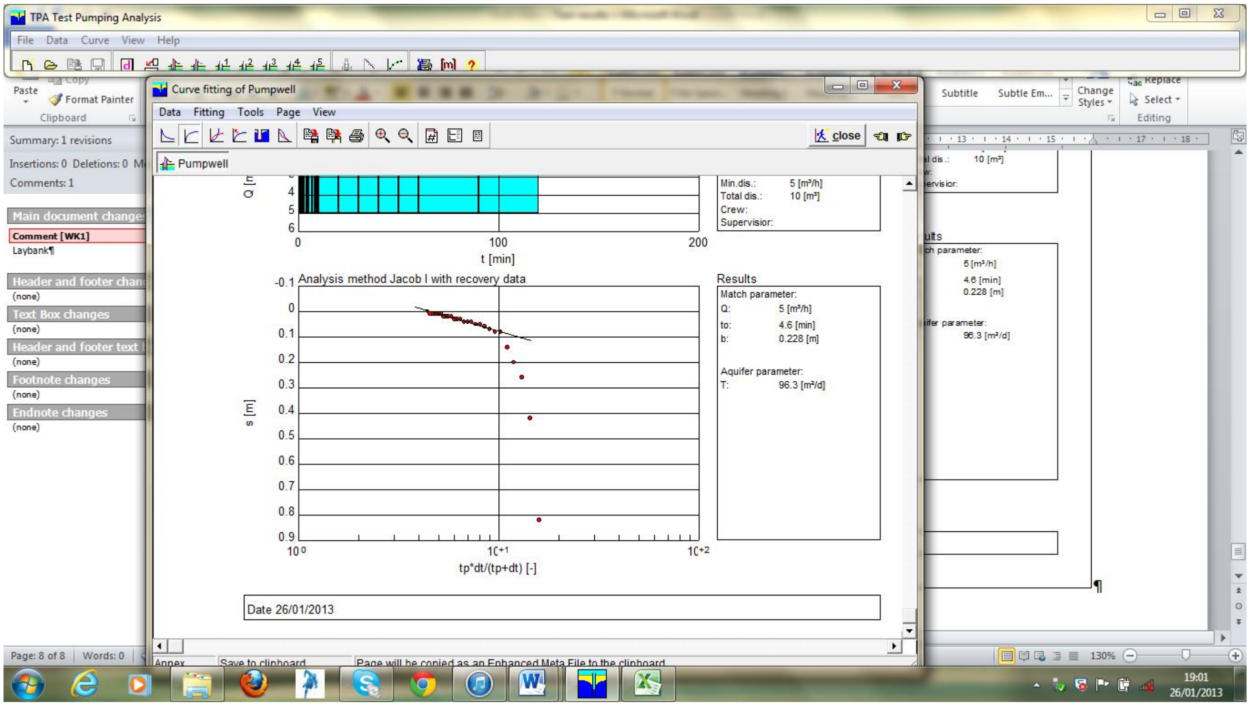
Main Test

Time	Date&Time	Time (h)	RWL	Draw-down	[mSi/cm]	pump.rate m³/h	time per 20 l in
1	12-Jun-09 10:01:00	**0.02**	11.50	4.78		5.0	
2	12-Jun-09 10:02:00	**0.03**	13.80	7.08		5.0	
3	12-Jun-09 10:03:00	0.05	15.58	8.86		5.0	
4	12-Jun-09 10:04:00	0.07	16.71	9.99		5.0	
5	12-Jun-09 10:05:00	0.08	18.00	11.28		5.0	
5	12-Jun-09 10:05:00	0.08	19.08	12.36		5.0	
7	12-Jun-09 10:07:00	0.12	20.90	14.18		5.0	
8	12-Jun-09 10:08:00	0.13	20.27	13.55		5.0	
9	12-Jun-09 10:09:00	0.15	20.55	13.83		5.0	
10	12-Jun-09 10:10:00	0.17	21.01	14.29		5.0	
20	12-Jun-09 10:20:00	0.33	21.08	14.36		5.0	
30	12-Jun-09 10:30:00	0.50	22.48	15.76		5.0	
40	12-Jun-09 10:40:00	0.67	23.00	16.28		5.0	
50	12-Jun-09 10:50:00	0.83	23.02	16.30		5.0	
60	12-Jun-09 11:00:00	1.00	22.96	16.24		5.0	
90	12-Jun-09 11:30:00	1.50	22.51	15.79		5.0	
120	12-Jun-09 12:00:00	2.00	20.00	13.28		5.0	
128	12-Jun-09 12:08:00	2.13	7.54	0.82			
129	12-Jun-09 12:09:00	2.15	7.14	0.42			
130	12-Jun-09 12:10:00	2.17	6.98	0.26			
131	12-Jun-09 12:11:00	2.18	6.92	0.20			
132	12-Jun-09 12:12:00	2.20	6.86	0.14			
133	12-Jun-09 12:13:00	2.22	6.80	0.08			
134	12-Jun-09 12:14:00	2.23	6.80	0.08			
135	12-Jun-09 12:15:00	2.25	6.79	0.07			
136	12-Jun-09 12:16:00	2.27	6.78	0.06			
137	12-Jun-09 12:17:00	2.28	6.77	0.05			
138	12-Jun-09 12:18:00	2.30	6.77	0.05			
139	12-Jun-09 12:19:00	2.32	6.76	0.04			
140	12-Jun-09 12:20:00	2.33	6.76	0.04			
141	12-Jun-09 12:21:00	2.35	6.76	0.04			
142	12-Jun-09 12:22:00	2.37	6.75	0.03			
143	12-Jun-09 12:23:00	2.38	6.75	0.03			
144	12-Jun-09 12:24:00	2.40	6.75	0.03			
145	12-Jun-09 12:25:00	2.42	6.74	0.02			
146	12-Jun-09 12:26:00	2.43	6.74	0.02			
147	12-Jun-09 12:27:00	2.45	6.74	0.02			
148	12-Jun-09 12:28:00	2.47	6.74	0.02			
149	12-Jun-09 12:29:00	2.48	6.73	0.01			

Pumped Well	Park Office
Start of Test	**12-Jun-09 10:00:00**
Start of Recovery	**12-Jun-09 12:08:00**
Duration of Test [h]	**2.0**
Duration of Recovery	**0.5**
RWL [m]	**6.72**
Residual Drawdown [m	**0.00**
P.I.D [m]	24
Depth of hole [m]	26

0.01666667

Figure 4-5: TPA Data Preparation Used in this Study



Min.dis.: 5 [m³/h]
Total dis.: 10 [m³]
Crew:
Supervisior:

Analysis method Jacob I with recovery data

Results
Match parameter:
Q: 5 [m³/h]
to: 4.6 [min]
b: 0.228 [m]

Aquifer parameter:
T: 96.3 [m²/d]

Date 26/01/2013

Annex | Save to clipboard | Page will be copied as an Enhanced Meta File to the clipboard

Figure 4-6: TPA Software Interface Used in this Study

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CHAPTER 5: RESULTS

5.1 GENERAL GEOLOGY

Section 5.1 addresses objective one which states; ‘To give a summary of the geology and a detailed lithostratigraphy of the study area’.

The Naukluft Mountains form the NNC made up of imbricated nappes of allochthonous Swakop and Witvlei groups and para-autochtonous Nama Group of the Southern Foreland (Miller, 2008). The complex has several thrust and nappe structures. The NNC forms a 68 kilometer long and 30 kilometer wide area of mostly dolomitic terrain (Miller, 2008, Viola et al., 2006) and measures about 750 meters in thickness (Korn and Martin, 1959). The NNC is divided into several nappes based on the composition and rock type. Each of the nappes of the NNC is made up of heterogeneous assemblage of sedimentary formations from shallow marine to tidal flat zones to fluvial conditions (Sylvester 2010); these are the Kudu Nappes which are mostly dolomites, the Dassie Nappes which are composed of limestone. At the slope of the mountains to the south of the complex, green shale, purple shale and white dolomite constitute the Pavian Nappes. The Zebra Nappes overlay the Kudu Nappes and are composed of quartzitic shale. The complex has a light brown cap carbonate at the top with the gritty sole dolomite being the base of the package as it slid into its current position on top of a dark grey Nama Limestone (Miller, 2008).

The sole dolomite has been mylonitized as a result of thrusting. This complex owes its origin to the evolution of the Southern Margin Zone. It was emplaced in five phases of thrusting D_1 to D_5 (Miller, 2008). D_1 and D_2 thrust phases saw the emplacement of the Zebra River, Tsabisis, Blanskranz and Remhoogte formations. D_3 was a folding event which resulted in the folding of the Zebra and Onis formations. D_4 thrusting resulted in dismembering of the Kudu-Dassie Nappe into Kudu, east and west Dassie as well as the South Pavian Nappes (Miller, 2008). D_5 thrusting was the final phase which saw the emplacement of allochthonous Naukluft Nappe Complex (Miller, 2008). Viola et al (2006) quoting Korn and Martin (1959) produced a cross section of the area as shown in Figure 5-1.

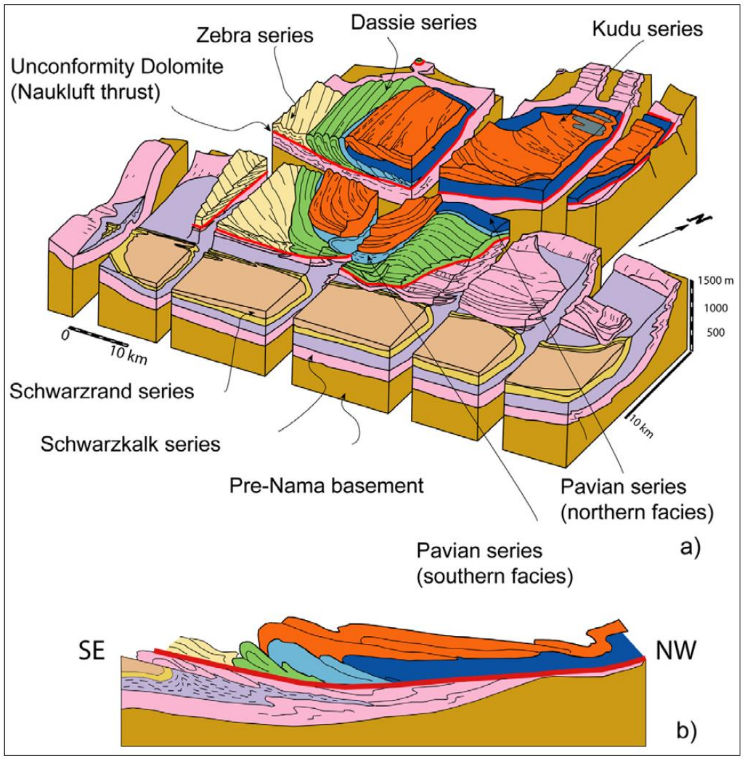


Figure 5-1: Cross Section of the Naukluft Mountains (Originally by Korn and Martin, 1969, modified by Viola et al, 2006)

The thrust zone forms the floor to the NNC and it consists of several distinct components; a massive ocre yellow weathering dolomite, a polymict gritty dolomite strongly foliated and a calc-mylonites and upper massive dolomite rarely found together in the field. The gritty dolomite is not the same everywhere; it differs in appearance and texture, and is in contact with the Nama Sequence. The gritty dolomite injections can be found in the hanging wall of the the Naukluft Nappe Complex lithologies.

5.2 LITHOSTRATIGRAPHY OF THE NAUKLUFT MOUNTAINS

In section 5.2 the lithologies of the Naukluft Mountains are described, addressing objective one which states: ‘To give a summary of the geology and a detailed lithostratigraphy of the study area’.

5.2.1 BASEMENT ROCKS

The Sinclair Supergroup is the oldest unit in the Naukluft Mountain area. According to Miller (2008) the Konkiep Group incorporates sedimentary and volcanic rocks in Helmeringhausen and Naukluft areas. Major outcrops of basement are in the south and west of the mountains.

5.2.2 NAUKLUFT NAPPE COMPLEX

The lithostratigraphy of the Naukluft Mountains in this study is described relying heavily on the work of Miller (2008) whose work on the NNC is an accumulation and summary of his work with reference to authors such as Korn and Martin (1959), Hartnady (1978) and Hoffmann (1994). The NNC is a stack of nappes and Miller (2008) reports seven such nappe units namely Rietoog, Northern and Southern Pavian, Western and Eastern Dassie, Zebra, Leopard as well as Kudu Nappe.

In his work Miller (2008) takes a closer look at the formations and members that make up the NNC. First is the Onis Formation, which is structurally one of the highest units in the NNC. It consists of massive dark grey dolomite overlain by dolomite and black well bedded oolitic limestone. Second is the Remhoogte Formation, which consists of greyish green parallel laminated phyllitic sub-greywacke and shale, deposited in deep waters. Two distinct carbonate layers occur on top of the formation, the lower of the layers consists of massive and often brecciated grey dolomite whereas the upper layer is made up of bedded to laminated limestone and coarse-grained, intraformational limestone breccias. Third is the Blasskranz Formation; it consists of four units. A basal shale unit, that overlies the limestone breccias of the Remhoogte Formation paraconformably, it is pale, calcareous and rhythmically laminated containing unsorted dropstones from pebble to boulder size. The unit resting immediately above is a brown micaceous quartzite and quartz-mica phyllite with few thin interbedded carbonate breccias lenses. The upper middle layer is a massive diamictite which rests on a sharply erosive base. The fragments of the diamictite range in size from sand to large angular blocks set in dark greenish grey sandy, shale, calcareous shale, marl and impure limestone. The upper most unit is the Tsugaub Volcanoclastic Member which contains interbedded layers of grey quartzite, laminated purple shale, green lapilli, matrix supported diamictite with carbonate and granite clasts. The shale contains granule and pebble-sized clasts of quartzites, quartz, granite, carbonate and feldspar. A cap carbonate overlies the Tsabisis Formation paraconformably. The lower part of the dolomite cap is massive with a wavy internal lamination, the upper part is thinly and evenly stratified with thin partings of purple shale that become thicker and more abundant as the formation grades into a rhythmically bedded succession of pink, laminated limestone and purple shale. The upper most unit of the Tsabisis Formation consists of thinly bedded siltstones with platy dolomite, dolomitic limestone and a few discordant breccias beds.

The fourth is the Noab Formation; the high energy equivalent of the Bullsport Formation consists of very thickly bedded to massive weathering dolomite, with three fold sub-divisions. The lower unit consists of grey to yellowish dolomite-limestone with pink to purple beds, cross-bedded sandy dolomite and minor brown dolomitic quartzite. The middle clastic unit on the other hand consist of thinly bedded, ripple-marked quartzite and green purple slate. The upper unit is made up of brown weathering dolomite, sandy as well as inter-bedded quartzite.

Bullsport Formation is the fifth and it is intensely imbricated. The basal part consists of purple shale and limestone. These rocks pass upward through a thin laminated limestone into a thick succession of well bedded dolomite with minor clastic rocks. The latter has three fold divisions. A lower dolomite containing layers with hummocky cross-bedding and ripple cross-lamination suggesting a sub tidal deposition environment. The overlaying clastic unit contains several meter thick cycles of white, ripple-marked quartzite and purple shale whereas the upper unit is made up of grey to white dolomite. The Neuras Member consists of a light coloured dolomite and quartzite.

The Zebra River Formation marks the sixth of the formations; it is an equivalent of the lower Nama Group made up of three conformable units. The Ubusis forms the basal unit. It is made up of quartzite and conglomerate. The Tsams Member follows, and it consists of dark grey dolomite and quartzite considered to be an equivalent of the Omkyk Member of the Zaris Formation, a constituent of the Nama Group. The final unit is the Lemoenputs Member made up of siltstone and shale with minor interbedded black limestone, grey quartzite and quartz-pebble conglomerate.

The second last formation is the Klipbokriver Formation. It rests uncorfomably on the Noab dolomite and consists of green, deep water shale with interbedded layers of carbonate debris-flow breccias. Aubschlucht Formation is the final formation. It is a minor unit that forms part of the southern Pavian Nappe and is made up of a sequence of arkosic sandstone, conglomerate and siltstone.

5.2.3 SOLE DOLOMITE

Faber (2009) refers to the Sole Dolomite as a widely debated component of the NNC. An observation that is true because there is no separating one from another. For the context of this study, and its underlying nature as either a water sealant feature or one that transmits, the Sole Dolomite is examined as a lithology and not for its structural and depositional character although these characteristics define constituents of what makes up the Sole Dolomite. It is referred to as the Unconformity Dolomite by Behr et al (1983) who suggested that its source were continental evaporate deposits. This assumption was previously widely accepted; however, Sylvester (2009) in his conclusion differs with previous authors based on the analysis of his work. A Sylvester (2009) report that the NNC Sole Dolomite does not originate from the Duruchaus formation as previously reported but that it is of similar age to the Damara orogenised dolomites. Sylvester (2009) further refers to work done by Miller (2008) to support his conclusion where $\delta^{18}O$ values from dolomites associated with the fault are low which is characteristic of burial dolomites. Contrary to previous studies on the NCC thrust (Sole Dolomite) by Viola et al (2006), Hartnady (1978), Korn and Martin (1959) and Munch (1978) as quoted by Sylvester (2009); he concluded that the fault surface is undulatory this was deduced by plotting GPS positions long its length and stereonet data the result of which showed that the fault changes in height and angle.

Miller et al (2008) in their study observed a significant range in the $\delta^{18}O$ values in the Sole Dolomite, with the leading edge showing a larger range than the trailing edge. Miller et al (2008) deduced that $\delta^{18}O$ values are characteristic of burial dolomites and secondary dolomitization is indicated by the presence of networks above and below the Naukluft Thrust zone. Further, Miller et al (2008) interpreted the large range in $\delta^{18}O$ values and variations in $\delta^{13}C$ vs. $\delta^{18}O$ patterns to be the result of interaction between the precursor to the Naukluft Thrust zone dolomites and fluids derived from different footwall lithologies and that $^{87}Sr/^{86}Sr$ isotope ratios indicated that some fluids were derived from the basement material.

The main mineral constituent of the Sole Dolomite is dolomite, distinguished in four generations, namely micritic dolomite, sparitic dolomite, third generation dolomite forming oriented overgrowths on the sparitic grains of the dolomites and fourth generation dolomite which forms small clear crystals on the walls of late tectonic fractures and pore spaces, it contains numerous fragments of different sizes as xenolithic rock fragments such as granites, granodiorites, gneisses and mica schists as well as autolithic rock fragments of albire-rich cherts, quartzitic and schistose rocks as well as varicoloured fragments (Behr et al., 1983).

The Sole dolomite is not of uniform nature (Sylvester, 2009) as shown in Figure 5-2 a, b c and d below.

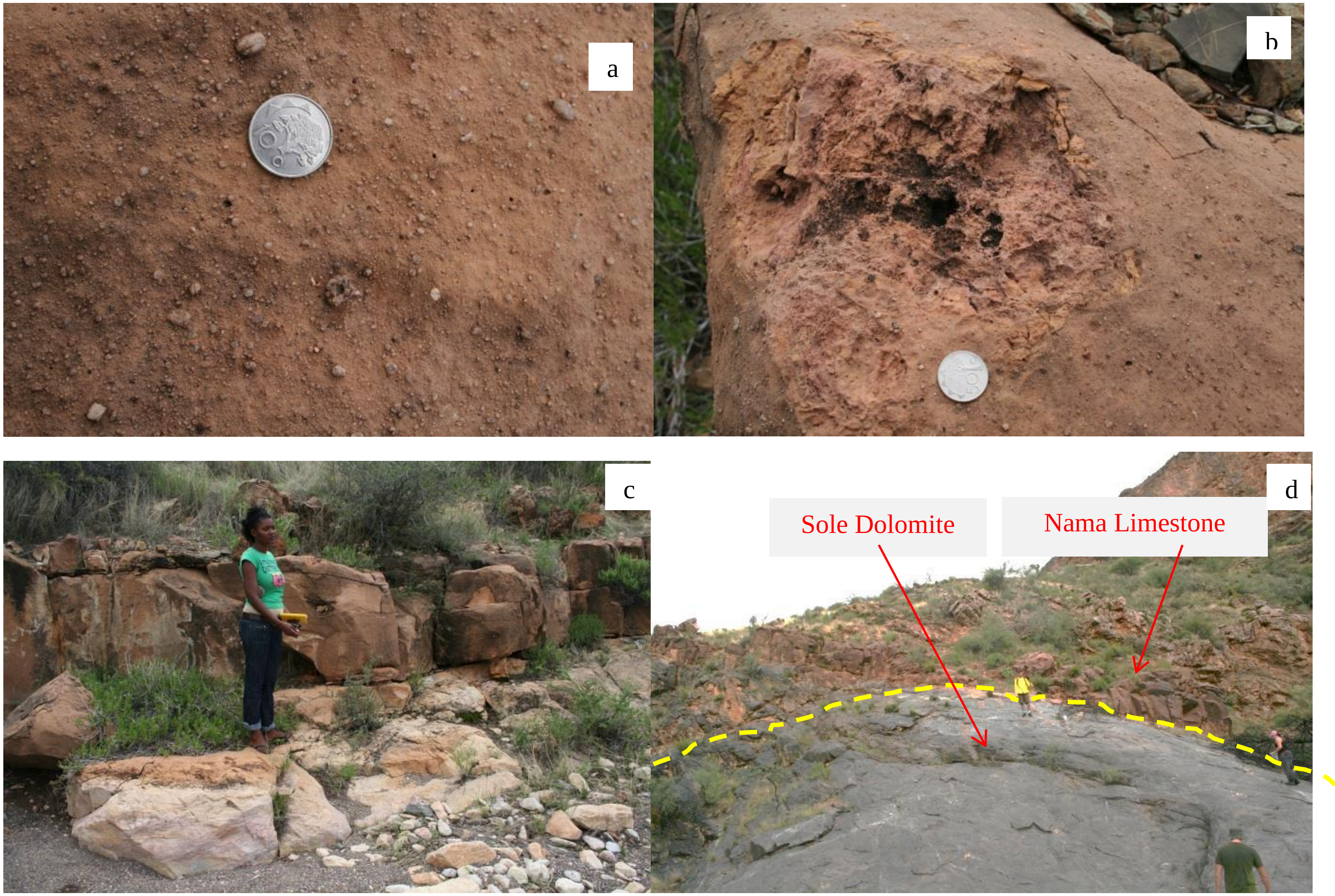


Figure 5-2: The Sole Dolomite (Images by Prof. Benjamin Mapani, 2009)

(a) Yellow ocre colored with gritty texture (b) observed xenoliths (c) fractured and jointed (d) thrust contact zone with the Nama Group limestone

The thrust zone forms the floor to the NNC and it consists of several distinct components; a massive ocre yellow weathering dolomite, a polymict gritty dolomite strongly foliated and a calc-mylonites and upper massive dolomite rarely found together in the field (Sylvester, 2009).

Behr et al (1983) report that the base of the Sole Dolomite is mylonitised and only a few centimetres in thickness and it grades downwards into the Nama Limestone and that the boundary between the mylonitised Nama Limestone and the Sole Dolomite is not sharp.

One can then describe the Sole Dolomite as composed of highly heterogeneous fragments, mylonitised and faulted and mainly dolomitic in composition.

5.2.4 NAMA GROUP

The Nama Group as narrated from the work of Gresse & Germs (1993) and Miller (2008) represent a succession deposited in the Nama Basin extending from Gobabis in the north to Vanrynsdorp in South Africa, some 1000 kilometres apart (Figure 5-3). The Nama Basin is divided into Zaris, Witputz and Vanryndorp basins by Gresse & Germs (1993) while in Namibia, Miller (2008) sub-divides the basin into sub-basins namely; a north eastern Witvlei Sub-basin, a north western Zaris Sub-basin and southern Witputz Sub-basin. The Nama Group is made up of the Kuibis Sub-group; which is made up of cratogenic and initial orogenic siliciclastics with carbonates, the Schwarzrand Sub-group; which is largely flych carbonates. With the first molasse sediments forming the upper layers as well as the Fish River Sub-Group which is mainly a molasse succession and the youngest of the sub-groups. Each sub-group comprises a characteristic lithological assemblage interrupted by occasional unconformities (Figure 5-4). (Gresse & Germes, 1993).

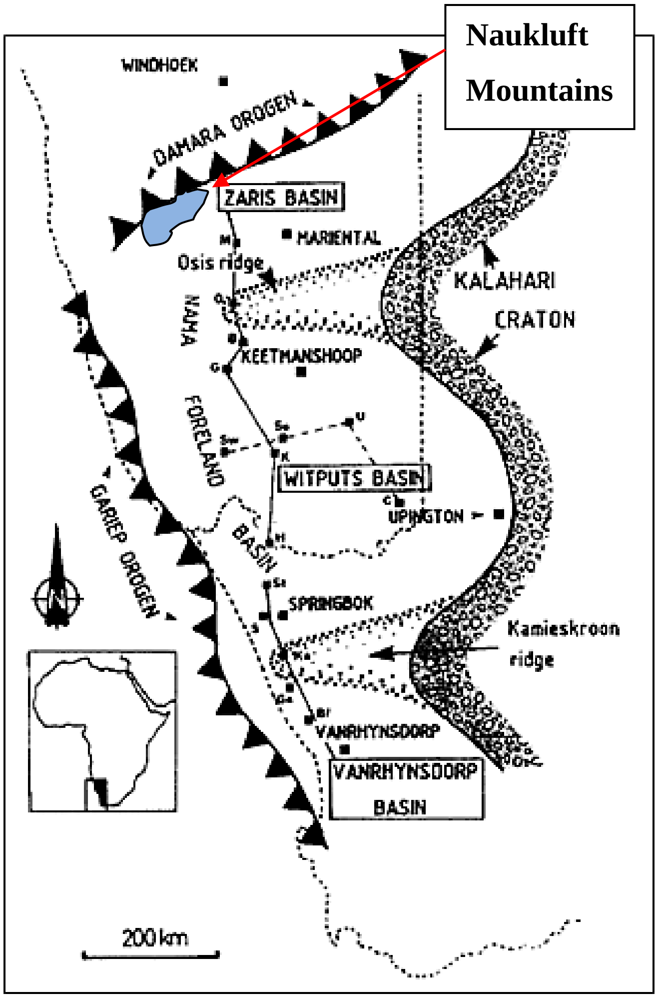


Figure 5-3: Distribution of the Nama Basin (After: Gresse & Germs, 1993)

There is inconsistency in the distributions of the group in its three sub-basins as some formations are absent in these basins. Miller (2008) states that in the Witvlei Sub-basin the Nama Group overlies the Witvlei Group paracomformably and only rocks of the Kuibis Group are found in this Sub-basin while in the Zaris and Witputz sub-basins the Nama Group uncomformably overlies basement, volcanic and sedimentary rocks of the Sinclair Group.

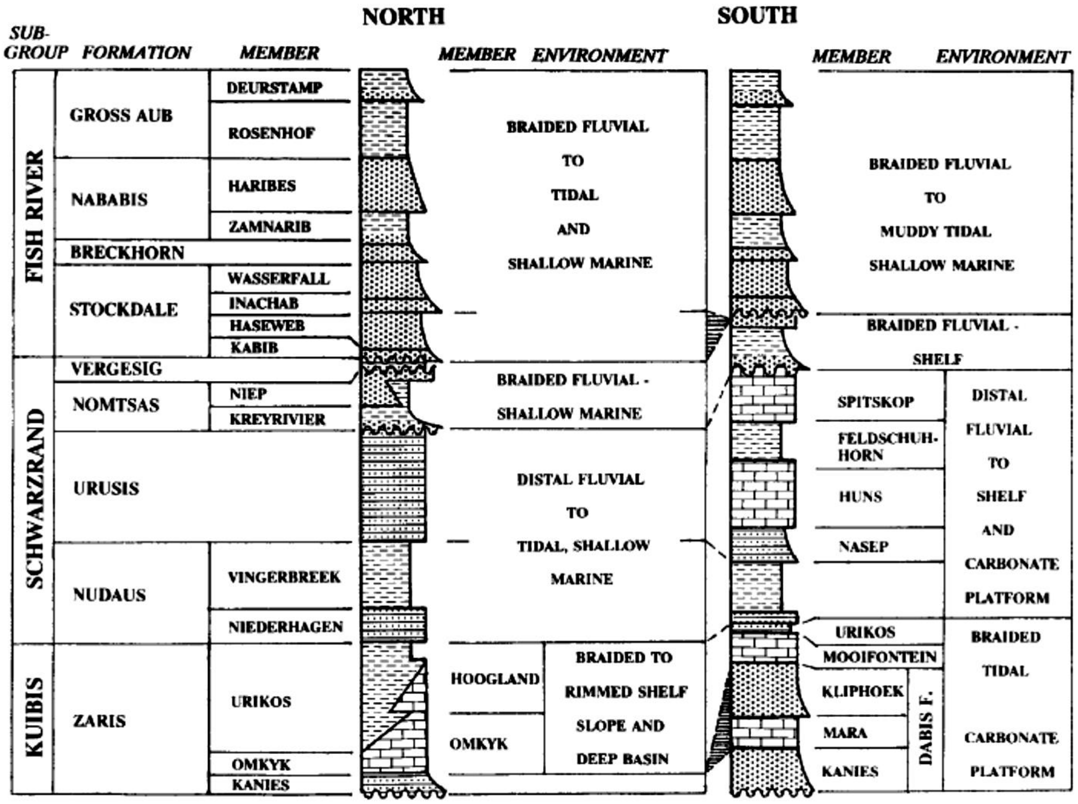


Figure 5-4: Generalized Stratigraphy of the Nama Group North and South of Namibia (After: Grasse & Germs, 1993)

The facies of the Kuibis and Schwarzrand groups reflect spatial changes in subsidence, water depth and the proximity to siliciclastic sediments (Miller, 2008). This in effect reflects the strong influence of the depositional environment on the rocks. Miller (2008) reports on three ramp facies, first being the inner ramp facies which formed in the shallowest water and includes sand shoals, thrombolytic and stromatolitic biostrome reef build ups and back barrier lagoonal and peritidal deposits. Tidal flat deposits include sand fenestral mudstones with clay pallets and mud cracks, shales, calcisiltite and fine-grained sandstone. Lagoonal deposits include calcilutite, siltstone, fine-grained sandstone and layers of small domal stromatolites. Second is the mid ramp facies rocks that were deposited between fair weather wave base and storm wave base. Resulting into plannar stratified beds, graded beds, hummocky cross-bedded layers and interbedded with shales and mudstones; very thinly to thinly bedded crobiolite, mottled laminate, interbedded carbonate mudstone, calcilutite, shale, calcarenite, and flat pebble intraclast conglomerates. Third is the outer facies whose deposits tend to be heterolithic and consist mainly of shales and very thinly to thinly bedded mudstones.

For the purpose of the this study, the Kuibis and Zaris sub-groups are of more interest because of their proximity to the Naukluft Mountains. Figure 5-5 outlines the approach taken to try and give an extensive description of parts of the Nama Group that have direct relation with the Naukluft Mountains particularly those deposited in the Zaris Sub-basin namely the Kuibis and Schwarzrand Sub-groups.

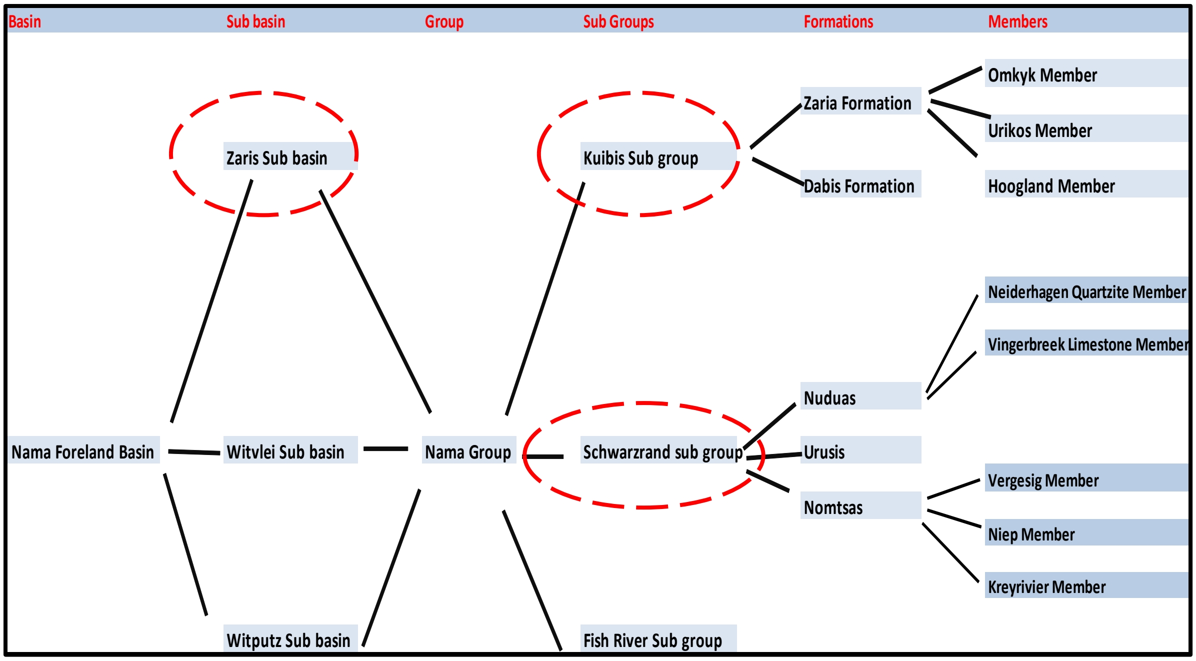


Figure 5-5: Outline the Approach Taken to Describe the Lithostratigraphy of the Nama Group

According to Miller (2008), the Kuibis Sub-group has a thickness that varies between 500 – 600 meters in the northern parts of the Zaris Sub-basin and up to 225 m in the Witzputz Sub-basin. Zaris and Dabis formations form the Sub-group. In the area around the Naukluft Mountains only the Zaris Formation is recorded. Miller (2008) describes three members that make up the Zaris Formation, namely Omkyk, Hoogland and Urikos members in order of their age. The Zaris Formation was deposited on an extensive carbonate ramp and platform that thickness northwards and north-westwards into the Damara Belt up to 500 m thick in the northwest.

The Omkyk Member is composed of black limestone referred to as the Schwarzkalk Limestone. With three intervals of approximate equal thickness, the lowest and uppermost being a resistant, upward-coarsening and upward-shoaling units (Miller, 2008). The middle unit is recessive and forms the lower part of the upward-coarsening sequence. Each interval grades upwards from a middle shoreface facies consisting of massive to hummocky cross-bedded calcisiltite, calcarenite grainstone overlain by thrombolitic/stromatolitic build ups. The lower unit is less extensive, occurs at the top of the succession of upward shoaling grainstones. The upper biostrome is the least extensive occurs at the top of the upper succession of upward shoaling grainstone and forms the top of the Omkyk Member, seen as tan coloured reefs (Miller, 2008). The Hoogland Member on the other hand, is mostly in the area south of the Naukluft Mountains almost 300 meters thick. The member consists of two major shoaling cycles of calcarenite and intraclast-ooid grainstone which passes laterally into finer grained and thinner calcarenites and eventually into shale. While the Urikos Member is made up of mid ramp mudstone dominated by heterolithic interbeds, outer ramp shale-dominated heterolithic interbeds and basinal green shales with rare interbedds (Miller, 2008).

The Schwarzrand Subgroup normally overlies the Kuibis Subgroup conformably or locally with a sharp contact (Gresse & Germs, 1993). Three formations and at least five sequences comprise the Schwarzrand Subgroup (Miller, 2008), with the Nudaus, Urusis and Nomtsas being the formations, given in order of their age. The Subgroup reaches up to 400 meters in thickness (Miller, 2008). It is dominated by thick limestones and terrigenous sediments decreasing in maturity towards the top, clastic sediments were deposited in distal fluvial to tidal and subtidal environments, supported by the occurrence of the tidal trace fossil diplocraterion (Grasse & Germs, 1993).

The Nudaus Formation is further constituted of the Niederhagen Quartzite and Vingerbreek Shale Members. Gresse & Germs (1993) speak of two possible glaciogenic intervals near the base of the Nudaus Formation. The Niederhagen, according to Miller (2008) consists of grey to greenish, medium-grained, planar laminated sandstone with interbedded siltstone and green shale. He further adds that the main sandstone facies has an erosive base, interbedded coarse-grained, cross-bedded sandstone layers, siltstones and shale beds as well as a shallow channel. In his description of the Vingerbreek Shale Member, Miller (2008) reports that, it consists largely of green shales which are interbedded 5 to 15 meters thick. Wave rippled sandstones and siltstones are interbedded with tabular bedded sandstones and shales.

The Urisis Formation as Miller (2008) describes, has significant differences in the sub-basins where it is deposited. In the Zaris Sub-basin it is made up of a sandy facies in the northeast that passes into a sandstone and green shale facies in the rest of the basin. The green shale facies is limited in the Witputs Sub-Basin before two inter bedded limestone units appear. Gresse and Germs (1993) add that cherts of possible volcanic origin occur in the Urusis Formation. The Nesep Sandstone, Huns Limestone, Feldschuhhorn Shale and Spitzkop Limestone members are not discussed in this study because they do not occur in the Zaris Sub-basin according to literature and as such have no direct relevance to the relationship that the Urisis Formation has with the Naukluft Mountains.

The Nomtsas Formation generally overlies the lower and middle Schwarzrand Subgroup unconformably, except north of Maltahohe and locally near Uis, north of the Osis Ridge, the reddish Nomtsas Formation changes from braided fluvial in the north to subtidal shale and sandstone with possible evaporites, and finally to thick subtidal green shale and limestone which locally contains stromatolites and the shelly fossil *Cloudina* (Gresse & Germs, 1993). It is rather special because it contains the first Cambrian trace fossils (Miller, 2008). The Formation is sub-divided into three members, Kreyrivier, Niep and Vergesig members. Miller (2008) describes the Kreyrivier Member to consist of conglomerate, grit and sandstone, which pass upward into marine siltstone, pebbly siltstone and shale, the coarsest conglomerate in erosional valleys are both matrix and clast supported, poorly sorted, consist of limestone and stromatolitic dolostone pebbles and boulders with minor sandstone and siltstone clasts. While the Niep Member is made up of well developed, trough cross-bedded sandstones and the Vergesis Member consist of interbedded sandstone and shale.

5.2.5 NAMIB GROUP

The youngest suite of rocks in the Naukluft Mountains are the Namib Group, that is made up of an often discontinuous and often localized succession of Cretaceous to recent deposits, that on a national scale extend from the Orange River in the south to the Kunene River in the north. They extend as far east as the great escarpment and locally further in land along westerly flowing rivers (Miller, 2008) of which the Tsondab and Tsauchab rivers are a part. The evolution of this group of rocks, according to Miller (2008) is hugely influenced by plaeoclimates with deposits like aeolian sandstones and gravels from fluviatile as major deposits.

One of the Aeolian sandstones is the Tsondab Sandstone Formation, which Miller (2008) describes to be largely composed of younger, unconsolidated dune sands of the Soussus Sand Formation and by fluvial and sheet wash fan deposits derived from the escarpment. Miller (2008) further adds that it consists of red brown, consolidated aeolinite with interbedded fluviatile units with a thickness of up to 220 m at Farm Escort. The aeolian facies is the largest component of the Tsondab Sandstone Formation, made up of fine- to medium-grained moderately to well sorted dune and sheet deposits whereas the fluviatile facies is made up of reddish sandstone, fluviatile units made up of finer grained arenites and highly dolomitic silts. The Tsondab Sandstone Formation of Miller (2008) was deposited by occasional floods similar to those presently observed in Sossusvlei and Tsoundabvlei. Conglomerates are also a major deposit in the Naukluft Mountain area. Miller (2008) reports that, they crop out west of Tsondabvlei and are of the Meso-Tsondab River. Miller (2008) observes a concomitant decrease in clast size from large cobbles and occasional boulders to coarse pebbly gravels. Clasts are largely rounded oblate to bladed dominated by pale blue grey and black limestone clasts derived from the NNC.

5.3 HYDROGEOLOGY

Section 5.3 addresses objective two, which states: ‘To classify and name aquifers, determine aquifer parameters of the aquifers that are in the study area’.

In Chapter 4, an attempt is made to describe in some detail the different rock units that are found within the study area. For the purpose of this study formations were described with focus on their capabilities and character as aquifers. In this regard what is highlighted are the rock formations as stratigraphic units rather than their structural character in the Naukluft Nappe Complex. In this

Chapter an attempt is made to describe the stratigraphic units in terms of their character as hydrogeological units, the objective is to establish how hydraulic parameters are influenced within the aquifer, to further support the significance of the Naukluft Mountains and highlight how surrounding aquifers benefit. Reference to geological structure will be made in terms of influence on the hydrogeology.

The term geohydro-stratifgraphy is used to describe the aquifers of the Naukluft Mountain area in relation to classified stratigraphic groups. For the purpose of this study classification of aquifers, each stratigraphic unit is generalized and treated as one aquifer as opposed to looking at different aquifers within that stratigraphic unit. Three aquifers will be discussed, namely the Namib Aquifer, Nama Aquifer and the Naukluft Karst Aquifer as they constitute the Naukluft Mountain (Figure 5-6).

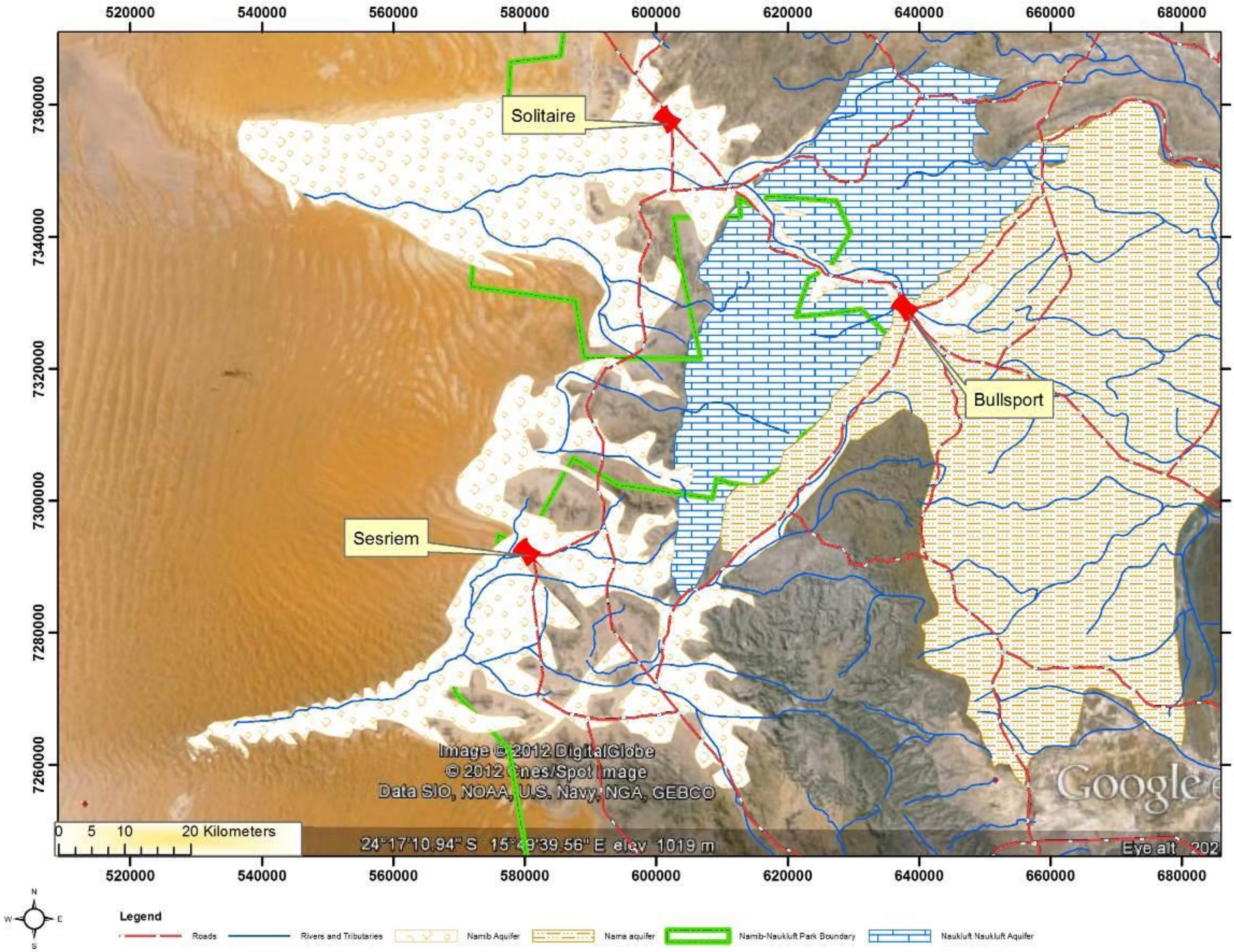


Figure 5-6: Aquifers of the Naukluft Nappe Complex (re-drawn from the Hydrogeology Map of Namibia)

5.3.1 NAMIB AQUIFER

Confined mainly to the Tsondab and Tsauchab rivers to the west and southwest of the Naukluft Mountains, is mostly composed of gravels, sandstone, conglomerate, dune sand and fluvial sediments which are mainly unconsolidated with fine to medium-sized grains that are well sorted. In addition, conglomerates with pebbles and clasts of different sizes form part of the aquifer and together with the aeolian sediment aspects the aquifer has capacity to store and transmit high volumes of water therefore the hydraulic parameters are excellent. A shown in Figure 5-6, the alluvial aquifers follows the drainage systems of the Tsondab and Tsauchab rivers whose tributaries emanate from the Naukluft Mountains as well as from the basement highs. The Namib Aquifer is the most utilized in the area, as tourism establishments tap from the aquifer established outside the Namib Naukluft Park boundary. Figure 5-7 shows the physical rock character of the aquifer.

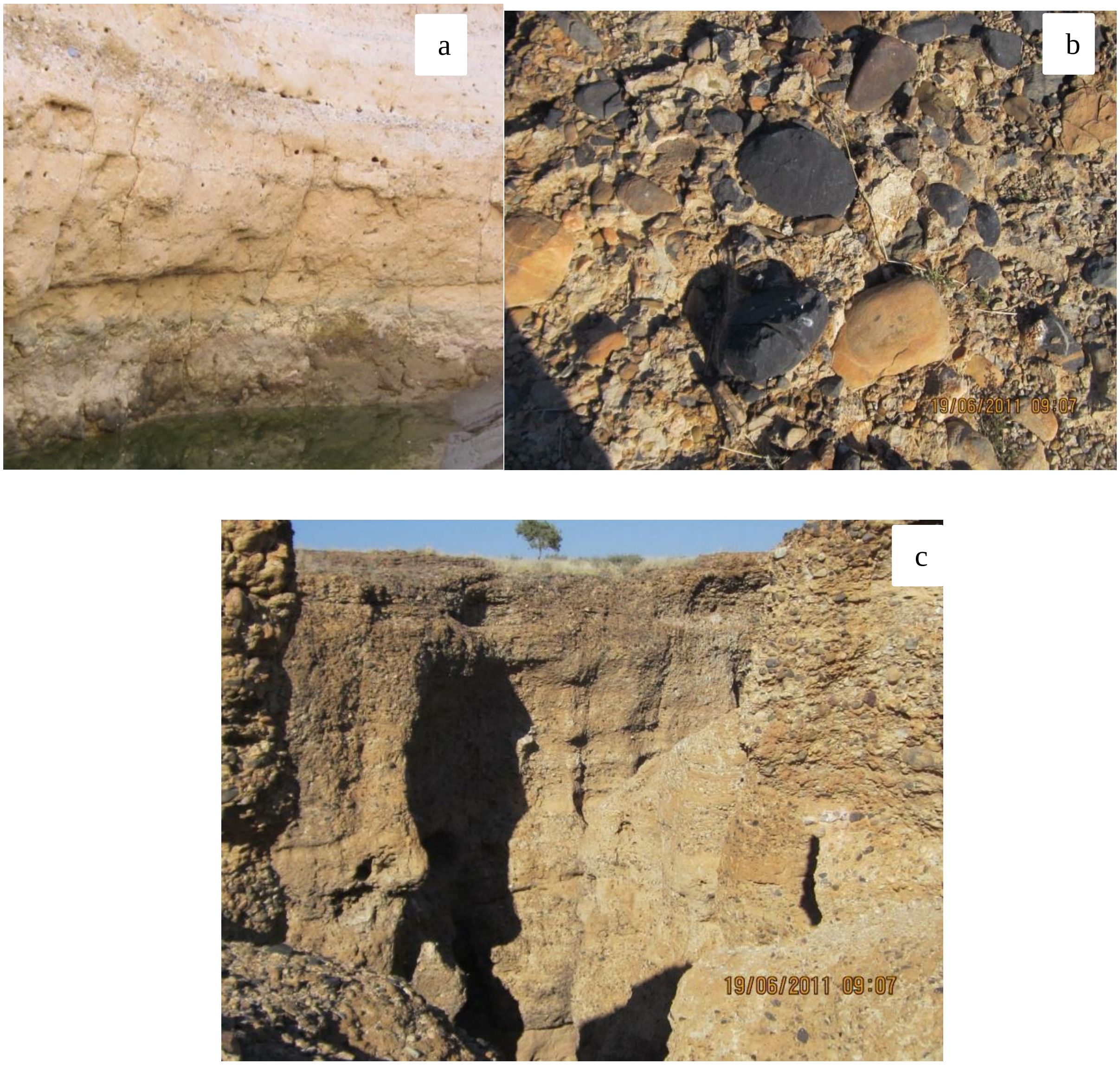


Figure 5-7: The Character of the Namib Aquifer
(a) Succession of fine and coarse alluvial sedimentation (b) & (c) conglomerates

5.3.2 NAMA AQUIFER

In general, this aquifer is composed of carbonates, sandstone, arenite, conglomerate and gritstone. Deposition cycles are very common within the aquifer. Shoaling cycles and interbedding as well as molasse sediments are an example. As a result there are variations in grain size and grading is not homogeneous. From the Kuibis and Zaris formations rock types are mainly limestone; calcarenites, quartzites, sandstone, shale, mudstone, conglomerate and gritstone are classed as part of these formations where the sandstone, conglomerate, quartzites, arenites and gritstones are aquifer horizons. In most cases, the aquifer horizons interbeds with aquitards (shale, siltstone and mudstone). In the aquifers, grains are cemented by fine sediment material that occupies pore spaces. Deposition relationships and pore cementation affect effective porosity and transmissivity of the aquifer which in this case is lower than the Namib Aquifer, to this effect more groundwater volumes are expected to flow in the Namib Aquifer than the Nama Aquifer. Furthermore inconsistencies in grading in turn affect general aquifer potential. Stratigraphic heterogeneity may also influence groundwater flow and storage because of the defined bedding between sandstone, shale and siltstone. The Nama Limestone on which the Naukluft Karst Aquifer was thrust is expected to be of moderately high groundwater potential, due to thrusting the Nama Limestone was recrystallized and therefore it has developed a secondary porosity in addition to a high fracture density which is expected to have developed of karstic features. The Sole Dolomite along the thrust plane separates the Naukluft Karst - and the Nama – Aquifer.

5.3.3 NAUKLUFT KARST AQUIFER

The Naukluft Karst Aquifer is structurally elevated compared to the other two aquifers in the study area. The rock types are largely carbonate comprising of dolomite and limestone, and also include phyllite, greywacke, shale, quartzite, conglomerate and siltstone. The carbonate rocks, conglomerate and quartzite are aquifers while phyllite and siltstone are aquicludes and aquitards. Because the aquifer is structurally elevated it is expected that dissolution features develop more rapidly in addition to faults and fractures due to deformation. As a result, a relatively evolved network of dissolution features has developed. This network of fractures contributes to high transmissivity. Formation of springs can be attributed to stratigraphic heterogeneities and basal thrusts between aquicludes and carbonate aquifers. The mylonitized Sole Dolomite also contributes to spring activity; as an aquitard groundwater above, it does not flow through instead it is forced out through ‘contact springs’.

The aquifer has two systems, this supported by Naude, (2010) whose work in the study area has shown that the spatial distribution of stable isotopes values in groundwater samples show a high variation indicating that boreholes tap from two distinct aquifer. The first is elevated and more exposed upper karst aquifer and the second is a lower seated presumably deep karst aquifer that is not directly interacting with atmospheric influences. The upper karst is thought to have high transmissivity and mixing off new waters as the aquifer is recharged as well as feeding the rivers. In the upper karst groundwater flow is locally variable, whereas the lower karst may have low conductivity with general flow more controlled on regional level south west ward where the age of the water is oldest getting into the alluvial in the south of the study area. A network of dissolution features including faults and fractures in the carbonates contribute to excellent aquifer transmissivity and storativity and in turn counter act the effect that aquicludes would have on these properties. Through the same network, large volumes of water are discharged during rainfall events resulting in surface run off that mainly follow the orientation of the rivers and streams that start from the mountains (Figure 5-8 a, b, c, d). Below the surface, interflow in the fractured zone becomes part of base flow.

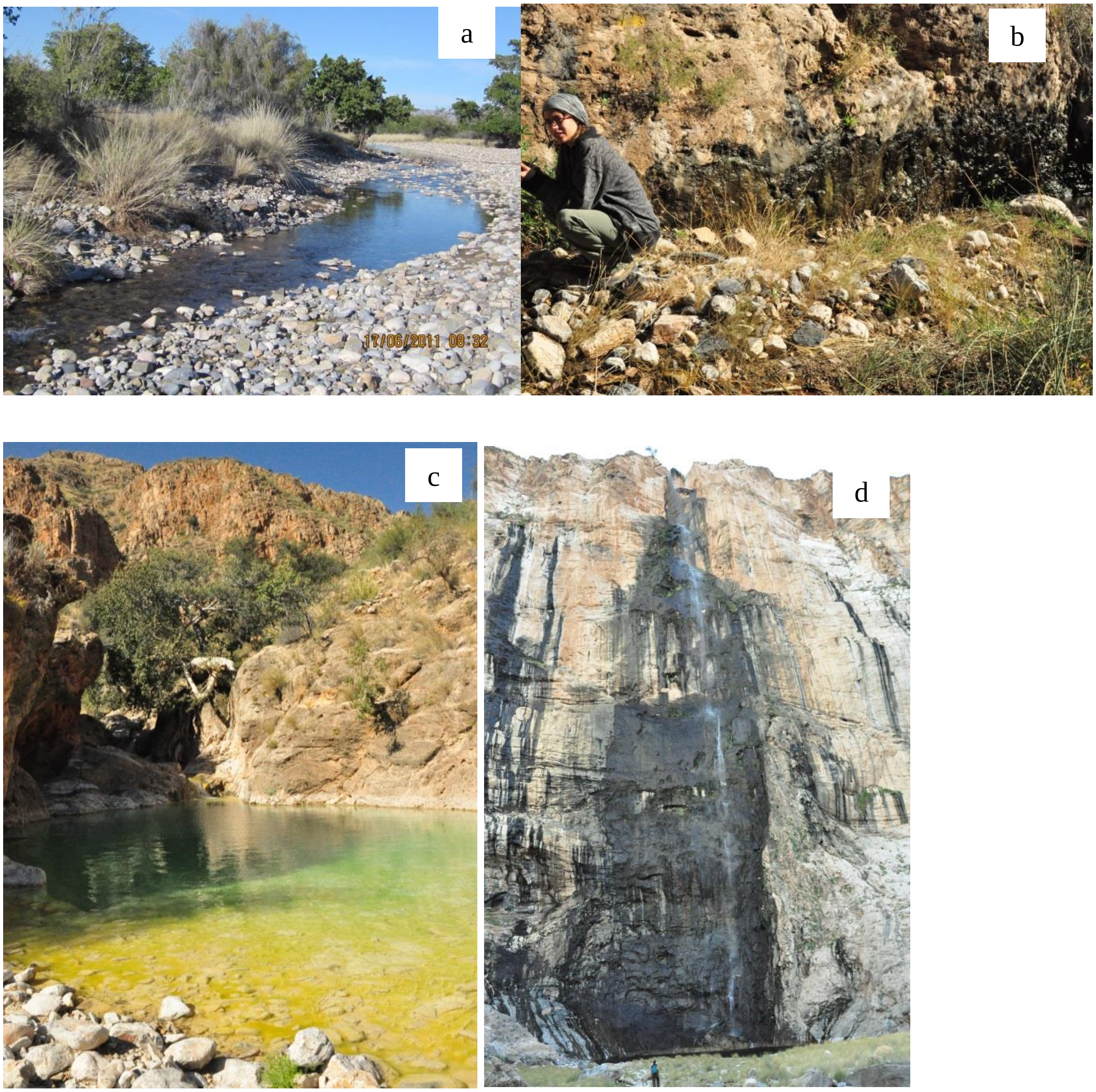


Figure 5-8: Surface and Spring Water Discharge in the Naukluft Karst Aquifer
(a) stream flow (b) seepage through lithological contact (c) spring discharge (d) waterfall

The thrust fault zone formed by the Sole Dolomite is also a conduit of groundwater flow as well as contributing to spring activity at the base of the Naukluft Karst Aquifer. This is due to a thin layer mylonite that acts as an aquiclude; it forces water out of the fracture zone. Further, in parts where the mylonite is fractured due to fault activity water percolates from the Sole Dolomite into the Nama Group Limestone (Figure 5-9).

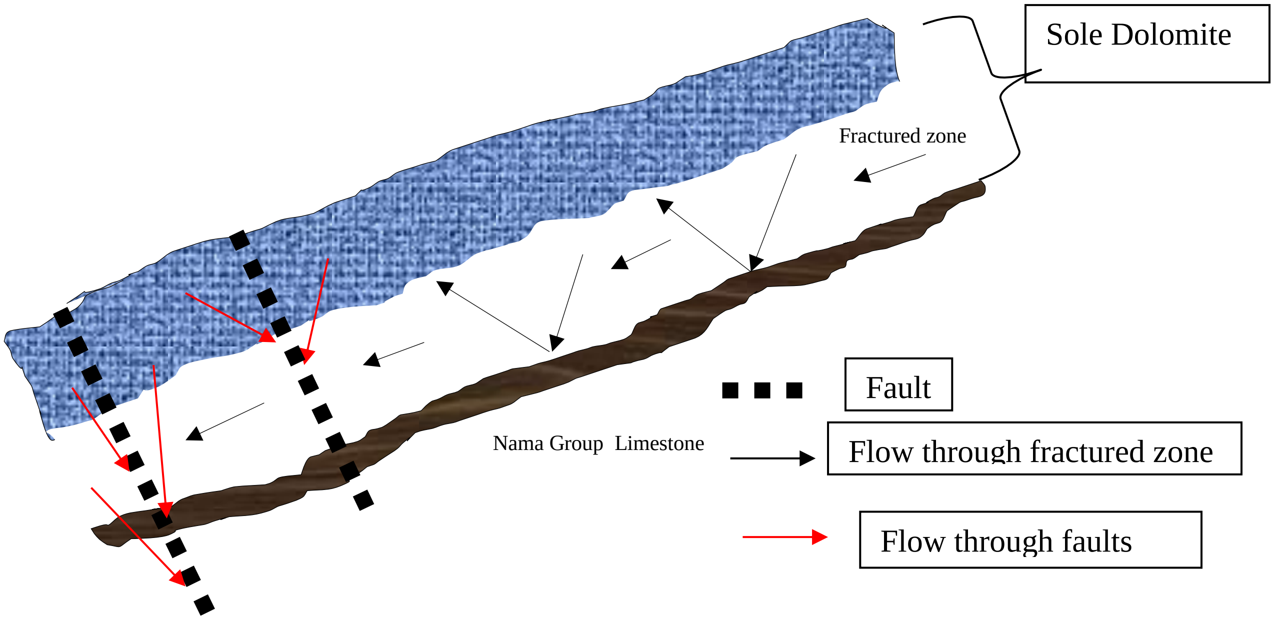
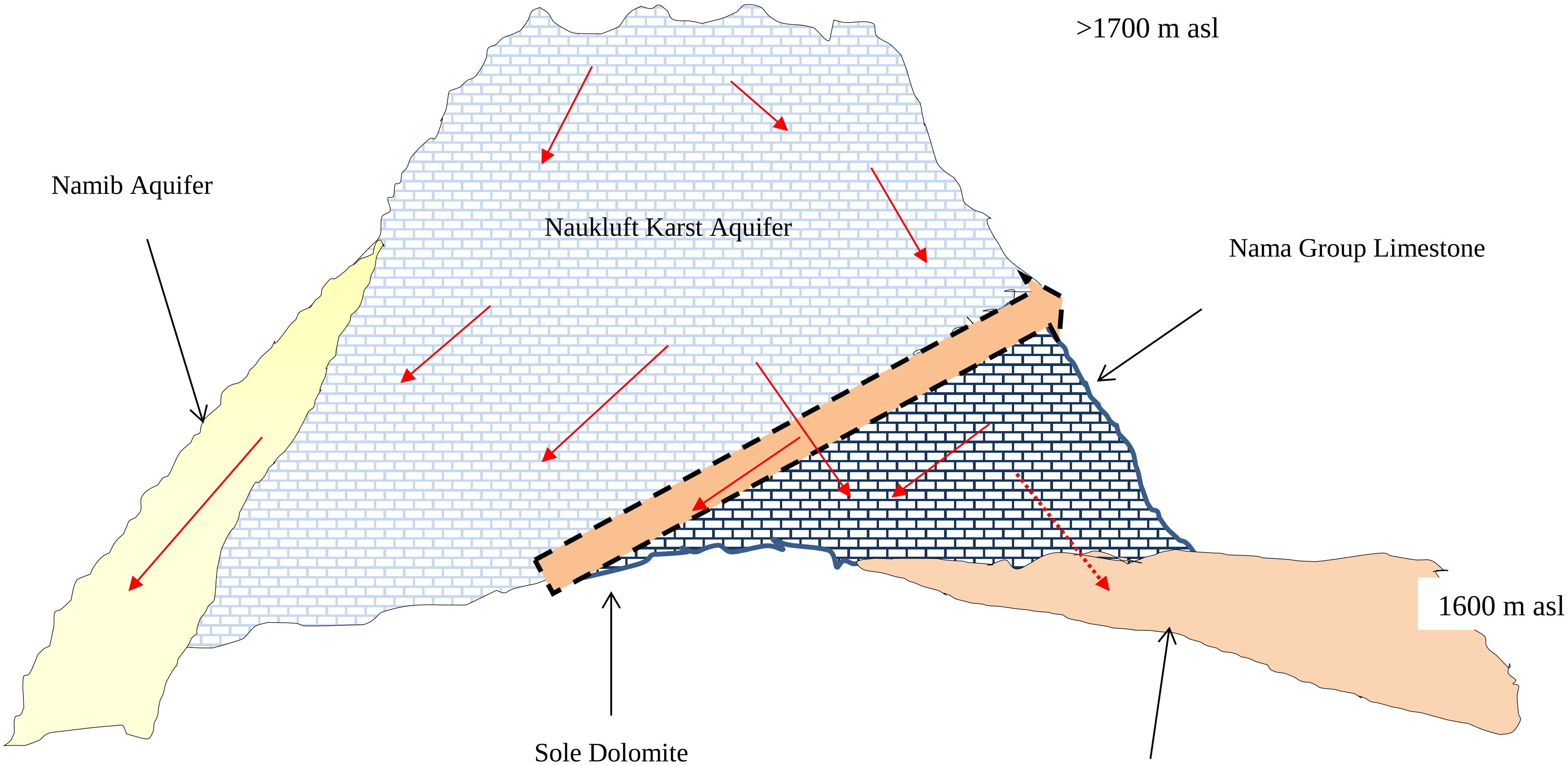


Figure 5-9: Groundwater Flow in the Sole Dolomite

Through these processes, groundwater from the upper karst aquifer flow into the lower karst aquifer, Namib and Nama aquifer. In Figure 5-10 an idealized aquifer interaction schematic diagram is shown.



Not to scale

Figure 5-10: Plain View of Idealized Interaction of the Naukluft Aquifer with Surrounding Aquifers

5.4 GROUNDWATER RECHARGE

Section 5.4 addresses objective three which states: ‘To estimate rainfall available for groundwater recharge and define the role that the Naukluft Mountains plays in groundwater recharge in the area’.

Previous studies on the study area have been aimed at- and have defined- the hydrochemistry characteristics of the groundwater, though some seasonal changes in chemistry have been observed. However, that does not preclude a general conclusion of the nature of the hydrochemistry in the area. This work is regarded as baseline for this present work. The level of at which the studies were carried out and the detail therein highlights this view. This underscores that recharge estimation in this study is also baseline contribution and more detailed work still needs to be done. This section will discuss rainfall trends, recharge and estimate recharge via CMB method.

5.4.1 RAINFALL TRENDS

Three rainfall records are available from the Naukluft area, the first from Ababbis east of Solitaire, and the second from Bullsport and last and third from Hauchabfontein, some 42 km south of Bullsport. Bullsport’s rainfall data spans 56 years (1950 – 2006) while Ababbis and Hauchabfontein start from 2002 and 2005 respectively. Trend analysis was done using the Bullsport data as it was the longest. Because the record does not include the 2008/2009 rainy season interpolation using data collected at Abbabis and Hauchabfontein was done (Figure 5-11 and Figure 5-12). An average rainfall figure of 170.36 mm/a was calculated from the Bullsport data, which for the purpose of this study is “study area rainfall” for the study area while, the “national average rainfall” for the area is pegged at 200 mm/a taken from the Accia Project data. However Boyer et al (2000), states that in comparison to the general desert environment rainfall can be significantly higher than the local or national average values used in this study. (This is mainly due to the elevation of the NNC, which rises to over 600 m above the surrounding areas. In Figure 5-12, shows that from 1962 to 1977, the study area received high rainfall over all, though seasonal variations are sharp in the sense that record high rainfall is followed by record low rainfall. The 15-year period of good rainfall is followed by 28 years of below national average rainfall. A period of good rains starts from 2005 onwards until the 2012-2013 season. There are 14 seasons on the record that are below 100 mm/a most of which can be classed as drought years. There appears to be a 10-to 20-year lag time between major droughts though variability is observed.

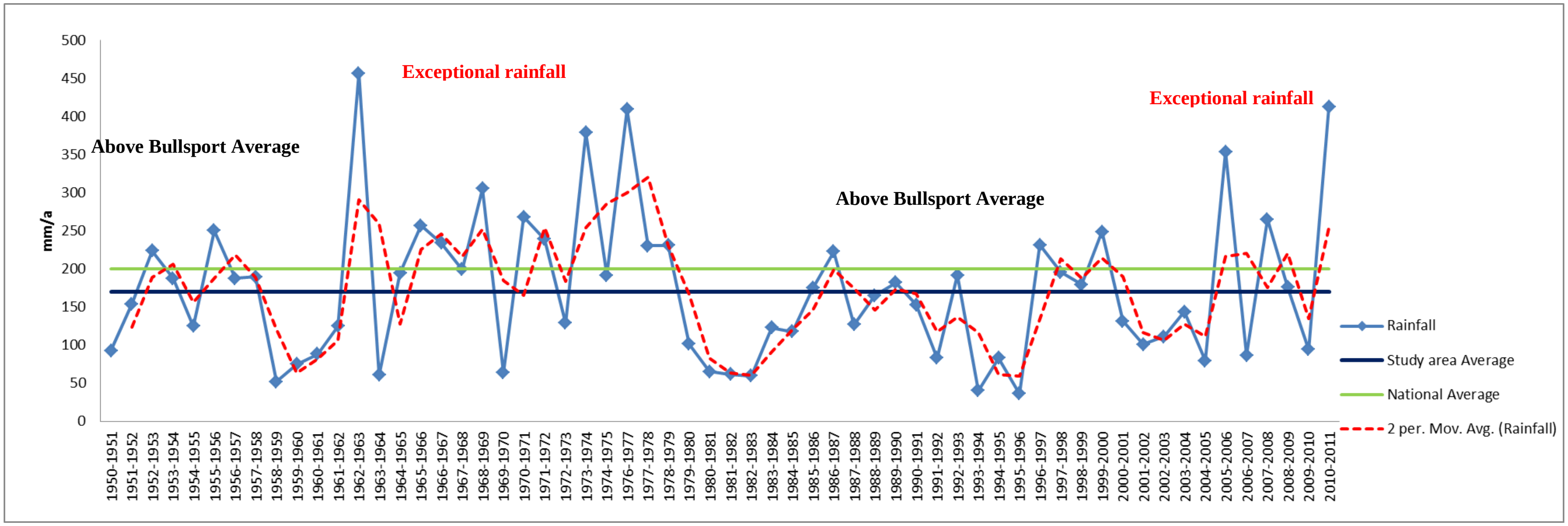


Figure 5-11: Presentation of Seasonal Rainfall, Bullsport-Ababbis Interpolation

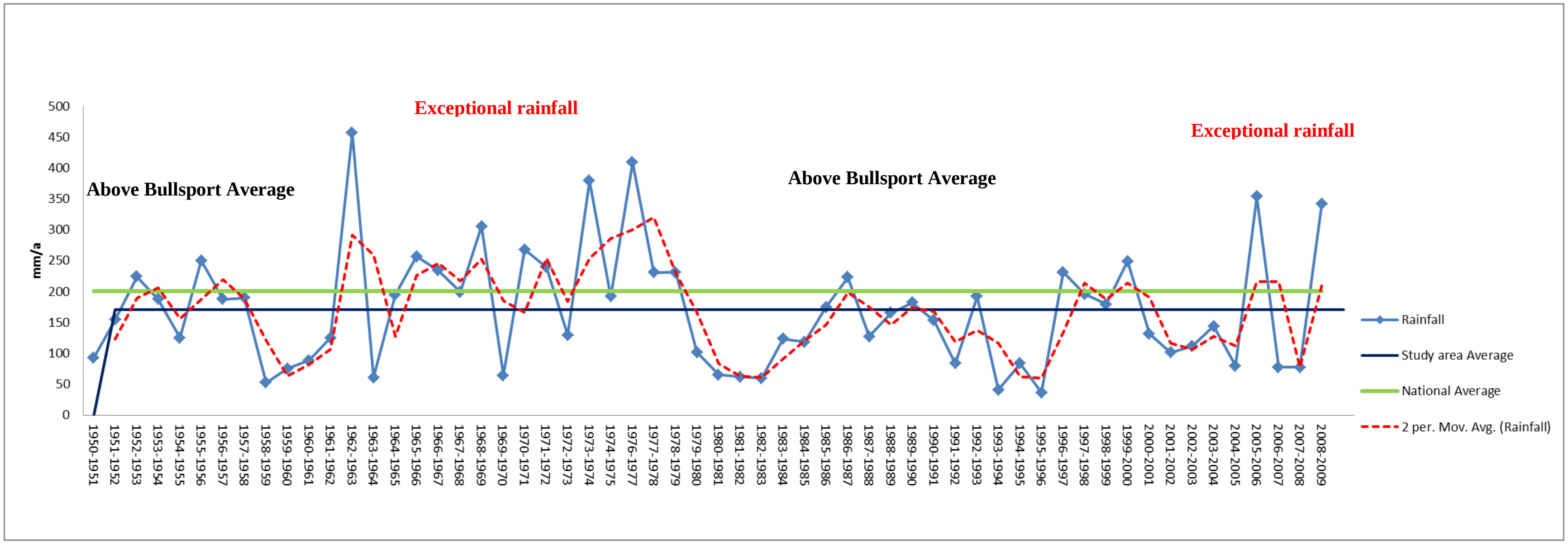


Figure 5-12: Presentation of Seasonal Rainfall, Bullsport-Hauchabfontein Interpolation

5.4.2 RECHARGE IN THE NAUKLUFT

Rainfall is the only source of major recharge and this is seasonal, as a consequence volumes available for recharge per season are variable. Establishing an estimate of quantities is viewed vital to guide water development planning to sustain current and suit future utilization. In understanding both recharge and flow within the aquifer system, recharge mechanisms especially in arid environments are important. The Naukluft Mountain area encompasses various possible mechanisms as it is a system that has karst, alluvial and structural features. In the Naukluft Karst Aquifer recharge is local and rapid inflow of rainfall through fractures, cavities, fault zones and sinkholes. Through the network of cavities and conduits large volumes of water is discharged from the upper karst as surface run-off into streams and springs. The lower karst is recharged through fault conduits that have developed in the sole dolomite. It is also true that springs continue to flow in the Naukluft Mountains (Karst aquifer), breaking at surfaces that correlate with thrusts; suggesting that the aquifer is in part structurally controlled, or at least in some of the areas where base flow follows faults and thrusts.

The Namib Aquifer is recharged directly by surface discharge from the Naukluft Karst Aquifer in addition to direct recharge from rainfall during the rainy season and via base flow during the dry season. It is expected that surface discharge and base flow benefits the Namib Aquifer more than the Nama Aquifer due to the geometry and flow pattern of the drainage system in the area.

5.4.3 GROUNDWATER RECHARGE ESTIMATION USING CHLORIDE MASS BALANCE (CMB) METHOD

Average chloride concentration has been calculated for precipitation samples collected during the 2008/2009 rainy season, the average value is used to calculate rainfall available for recharge at sampled boreholes during the same sampling season. Using the study area average rainfall of 170.36 mm/a calculated using the Bullsport data and the national average rainfall of 200 mm/a for the area. Results were computed in excel and are presented in Table 5-1 and Table 5-3. Employing the CMB estimation formula, Based on the computed results show an estimated range of 0.41 to 24.43 mm/a which translates to 0.24 to 14.34% of received rainfall for the season of 2008/2009 for both the local and national average. results do not factor surface stream losses.

In Figure 5-13 below the results are mapped across the study area. It is observed that the Naukluft Karts Aquifer is an area where there is moderately high rainfall available for recharge compared to the Namib and Nama aquifers. There are isolated areas in the Namib aquifer that have moderately high rainfall available for recharge; it is assumed that these areas have outcrops of basement rocks. However actual recharge is expected to be relatively lower for the Naukluft Karst Aquifer due to high losses due to surface discharge.

Table 5-1: Anion Results from Precipitation Samples of 2008/2009

Sample No		Clwp
17	NK09-3p125d	0.33
18	NK09-3p130d	0.35
19	NK09-3p144d	0.79
51	NK09-3p135d	2.06
112	NK09-3P117d	3.70
113	NK09-3P118d	0.20
114	NK09-3P119d	0.80
115	NK09-3P121d	1.50
116	NK09-3P124d	0.20
117	NK09-3P134d	0.90
Average concentration		1.08

Table 5-2: Computed Results of Rainfall Available for Recharge

Sample No	**Clgw**	P*Clwap (local average)	**Q**	**%**	P*Clwap (national average)	**Q**	**%**
Identification	**mg/l**						
NK09-3b23d	7.53	183.99	24.43	14.34	216.00	28.69	14.34
NK09-3b26d	45.35	183.99	4.06	2.38	216.00	4.76	2.38
NK09-3b37d	62.48	183.99	2.94	1.73	216.00	3.46	1.73
NK09-3b71d	74.45	183.99	2.47	1.45	216.00	2.90	1.45
NK09-3b67d	33.43	183.99	5.50	3.23	216.00	6.46	3.23
NK09-3b72d	19.42	183.99	9.47	5.56	216.00	11.12	5.56
NK09-3b93d	27.13	183.99	6.78	3.98	216.00	7.96	3.98
NK09-3b101d	31.31	183.99	5.88	3.45	216.00	6.90	3.45
NK09-3b105d	33.43	183.99	5.50	3.23	216.00	6.46	3.23
NK09-3b106d	21.21	183.99	8.67	5.09	216.00	10.18	5.09
NK09-3b112d	15.04	183.99	12.23	7.18	216.00	14.36	7.18
SOLO9-3b11d	117.31	183.99	1.57	0.92	216.00	1.84	0.92
ARAB1509-3b05	61.96	183.99	2.97	1.74	216.00	3.49	1.74
NK09-3b34d	210.28	183.99	0.87	0.51	216.00	1.03	0.51
NK09-3b35d	152.63	183.99	1.21	0.71	216.00	1.42	0.71
NK09-3b39d	124.72	183.99	1.48	0.87	216.00	1.73	0.87
NK09-3b40d	443.78	183.99	0.41	0.24	216.00	0.49	0.24
NK09-3b45d	21.79	183.99	8.44	4.96	216.00	9.91	4.96
NK09-3b46d	40.79	183.99	4.51	2.65	216.00	5.30	2.65
NK09-3b69d	146.95	183.99	1.25	0.73	216.00	1.47	0.73
NK09-3b74d	116.61	183.99	1.58	0.93	216.00	1.85	0.93
NK09-3b77d	164.10	183.99	1.12	0.66	216.00	1.32	0.66
NK09-3b79d	72.56	183.99	2.54	1.49	216.00	2.98	1.49
NK09-3b110d	23.38	183.99	7.87	4.62	216.00	9.24	4.62
NK09-3b133d	298.93	183.99	0.62	0.36	216.00	0.72	0.36
NK09-3b140d	20.90	183.99	8.80	5.17	216.00	10.33	5.17
NK09-3b141d	30.29	183.99	6.07	3.57	216.00	7.13	3.57

Table 5-3: Computed Results of Rainfall Available for Recharge (cont.)

Sample No Identification	Clgw mg/l	P*Clwap (local average)	Q	%	P*Clwap (national average)	Q	%
NK09-3w97d	36.79	183.99	5.00	2.94	216.00	5.87	2.94
NK09-3w147d	74.77	183.99	2.46	1.44	216.00	2.89	1.44
NK09-3B08d	85.20	183.99	2.16	1.27	216.00	2.54	1.27
NK09-3B10d	38.60	183.99	4.77	2.80	216.00	5.60	2.80
NK09-3B13d	278.00	183.99	0.66	0.39	216.00	0.78	0.39
NK09-3B14d	364.20	183.99	0.51	0.30	216.00	0.59	0.30
NK09-3B32d	225.00	183.99	0.82	0.48	216.00	0.96	0.48
NK09-3B33d	232.40	183.99	0.79	0.46	216.00	0.93	0.46
NK09-3B41d	140.00	183.99	1.31	0.77	216.00	1.54	0.77
NK09-3B42d	121.00	183.99	1.52	0.89	216.00	1.79	0.89
NK09-3B58d	26.00	183.99	7.08	4.15	216.00	8.31	4.15
NK09-3B59d	37.00	183.99	4.97	2.92	216.00	5.84	2.92
NK09-3B60d	49.00	183.99	3.75	2.20	216.00	4.41	2.20
NK09-3B62d	51.00	183.99	3.61	2.12	216.00	4.24	2.12
NK09-3B64d	72.00	183.99	2.56	1.50	216.00	3.00	1.50
NK09-3B65d	58.00	183.99	3.17	1.86	216.00	3.72	1.86
NK09-3B70d	26.00	183.99	7.08	4.15	216.00	8.31	4.15
NK09-3B73d	130.00	183.99	1.42	0.83	216.00	1.66	0.83
NK09-3B75d	132.00	183.99	1.39	0.82	216.00	1.64	0.82
NK09-3B76d	114.00	183.99	1.61	0.95	216.00	1.89	0.95
NK09-3B85d	37.00	183.99	4.97	2.92	216.00	5.84	2.92
NK09-3B86d	36.00	183.99	5.11	3.00	216.00	6.00	3.00
NK09-3B123d	123.00	183.99	1.50	0.88	216.00	1.76	0.88
NK09-3B127d	109.00	183.99	1.69	0.99	216.00	1.98	0.99
ZAIS09-3B04d	61.80	183.99	2.98	1.75	216.00	3.50	1.75
NK09-3B13d	22.50	183.99	8.18	4.80	216.00	9.60	4.80
NK09-3B51d	17.00	183.99	10.82	6.35	216.00	12.71	6.35
NK09-3B109d	32.30	183.99	5.70	3.34	216.00	6.69	3.34
NK09-3B113d	40.50	183.99	4.54	2.67	216.00	5.33	2.67
NK09-3B122d	182.00	183.99	1.01	0.59	216.00	1.19	0.59
KLIP09-3B03d	178.40	183.99	1.03	0.61	216.00	1.21	0.61

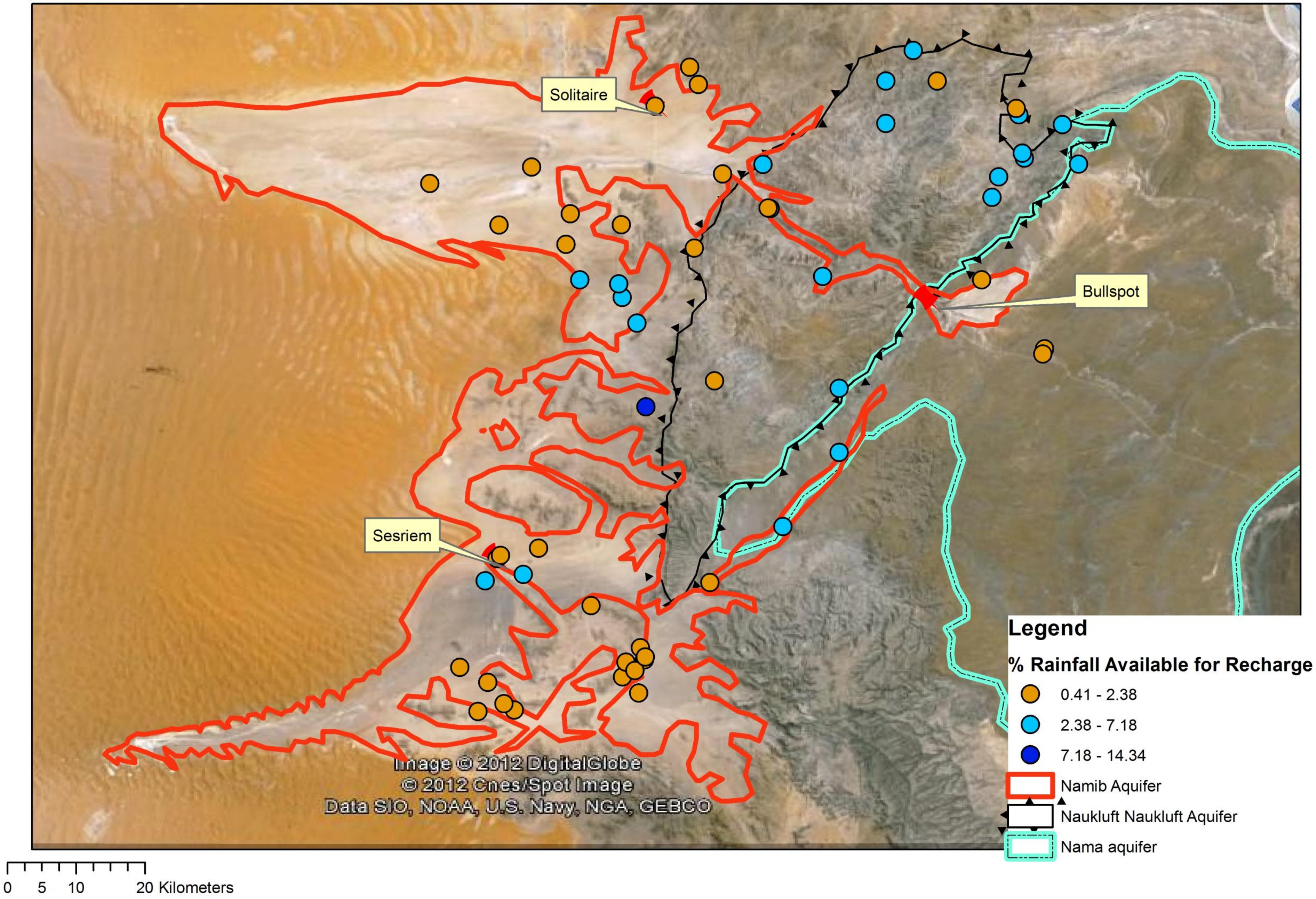


Figure 5-13: Distribution of Rainfall Available for Recharge over the Study Area

5.5 TEST PUMPING EVALUATION

Reconnaissance or exploratory test pumping was conducted at the following locations:

- Escort (Borehole) - Granite basement crystalline aquifer;
- Leybank (Borehole) - Nama sandstone aquifer;
- Naukluft park office (Borehole) - carbonate aquifer;
- Solitaire (Borehole) - Alluvial aquifer; and
- Zais (old well)-Carbonate aquifer.

Pump tests were conducted in the study area so as to have a quantitative figure on the four main types of aquifers: namely the crystalline basement, the dolomite/carbonate aquifers; the alluvial aquifers and the sandstone aquifers. The pump tests were constrained by the budget available for the project, and therefore only a few strategic sites were selected. Further, only main discharge tests were conducted. There were no observation boreholes during test pumping.

Locations are mapped in Figure 5-14

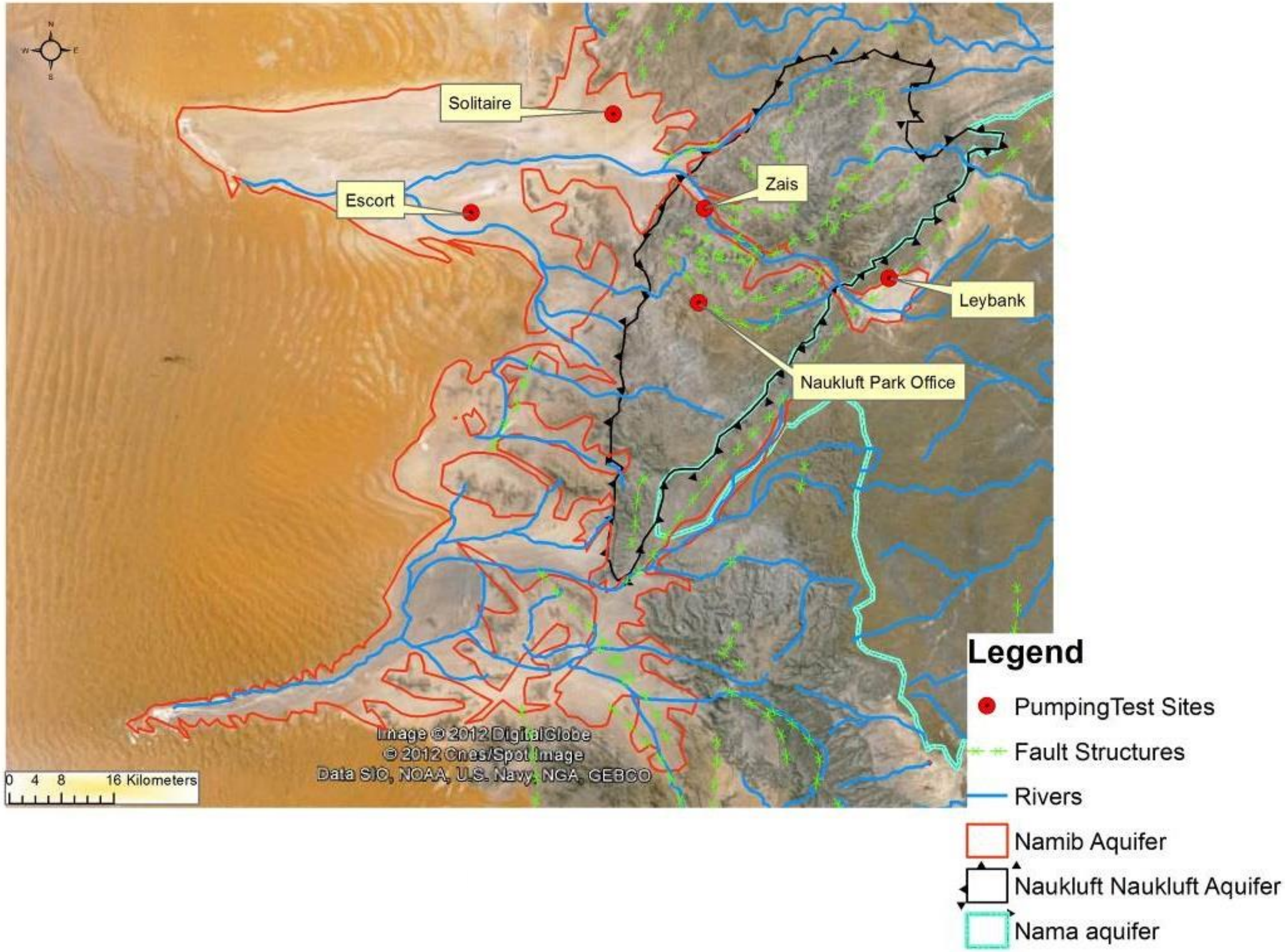


Figure 5-14: Location of the Test Pumping Sites in the Study

Test pumping at Leybank was carried out on a production borehole (depth 41 m) supplying the farm house, already installed with a submersible pump and was not heavily pumped due to low water requirement. The borehole is assumed to be situated in quartzite of the Nama Aquifer. The team was able to connect the generator to the pump already placed in the borehole because it was too risky to pull the pump out due to the orientation of the casing in the borehole.

The borehole was pumped at 1.5 m^3/h (the pumping rate of the pump installed in the borehole with an unknown inlet depth) with a rest water level of 28.42 m bgl. Pumping lasted for a period of 5 hours until a sudden sharp drawdown in water level was observed. The “sudden” drawdown of water level is inferred to be that the capacity of the water bearing structure was exceeded by the pumping rate (Figure 5-15). After 5 hours a drawdown of 12.62 m is calculated. The borehole recovered 95% 5 hours after pumping was stopped, further took an additional 24 hours to reach 99% recovery.

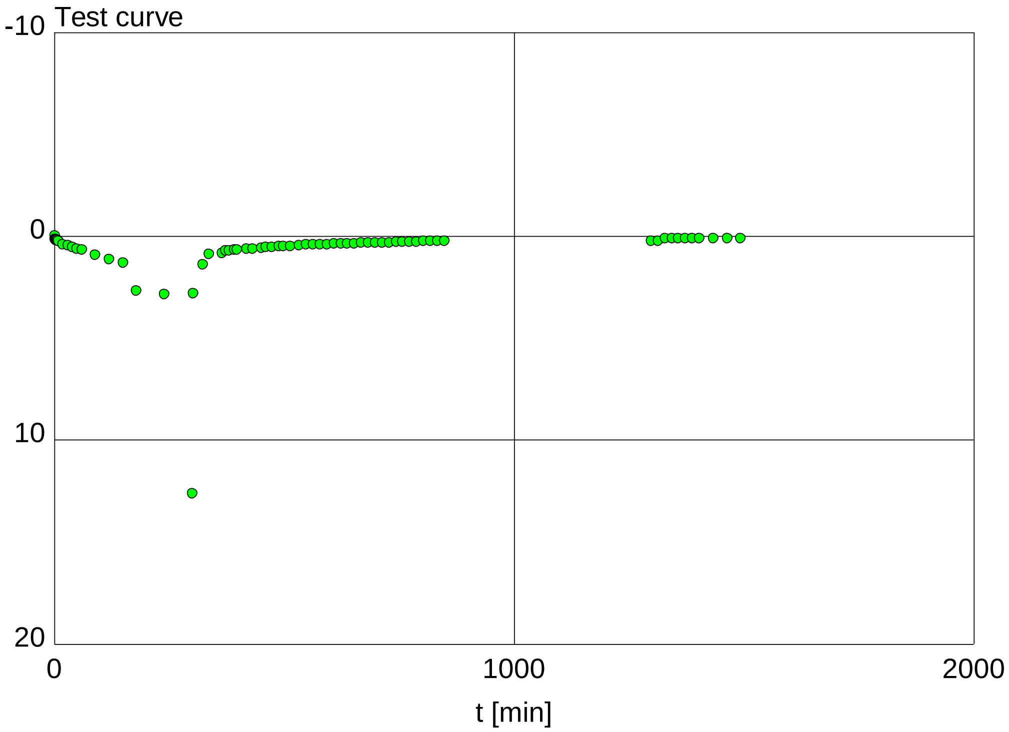


Figure 5-15: Time-Drawdown Plot of Leybank Borehole

The pump testing demonstrated that the aquifer hosted in the crystalline rocks of the Nama Group, cannot sustain the pumping rate over prolonged periods of time, and is rather regarded to be “low” in potential. Using Theis’ method in TPA software (Bardenhagen, 2000) transmissivity ranges from 4.1 m^2/d, (Figure 5-16).

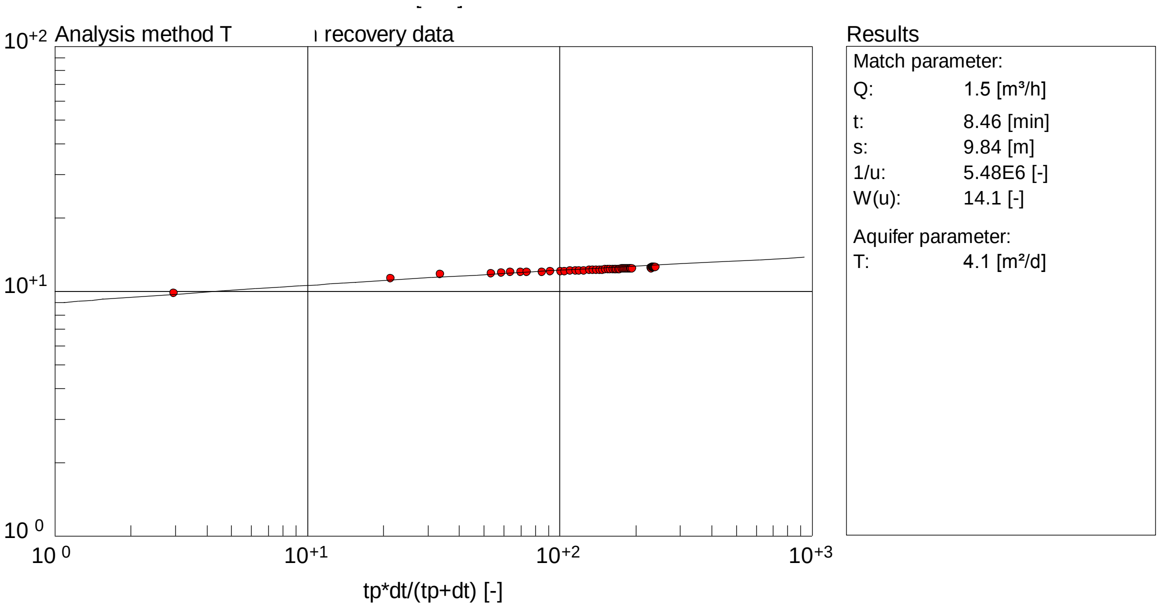


Figure 5-16: Test Pumping Data Analysis using Theis Method: Leybank Borehole

At the Naukluft Park Office pumping test was conducted in one of two production boreholes. The borehole is situated in the Naukluft Aquifer. The second borehole was installed with a diesel mono pump hence it could not be used as a piezometer in this test. The borehole (26 m) was already equipped with a pump and it had to be removed so that the project pump could be used, lowered to a depth of 24 m.

The rest water level at the beginning of the test was 6.72 m bgl, a rate of 5 m^3/h was applied. Pumping phase lasted for 2 hours before the water level reached the pump inlet depth, recovery phase was started immediately after. The test curve shows that the drawdown started to stabilize after 20 minutes of pumping (Figure 5-17). A drawdown of 13.28 m is calculated. The borehole recovered 99% 20 minutes after pumping was stopped. The test pumping results show that although high abstraction rates could not be applied on this borehole due to capacity of water bearing fractures, recovery was rapid which indicates relatively good potential.

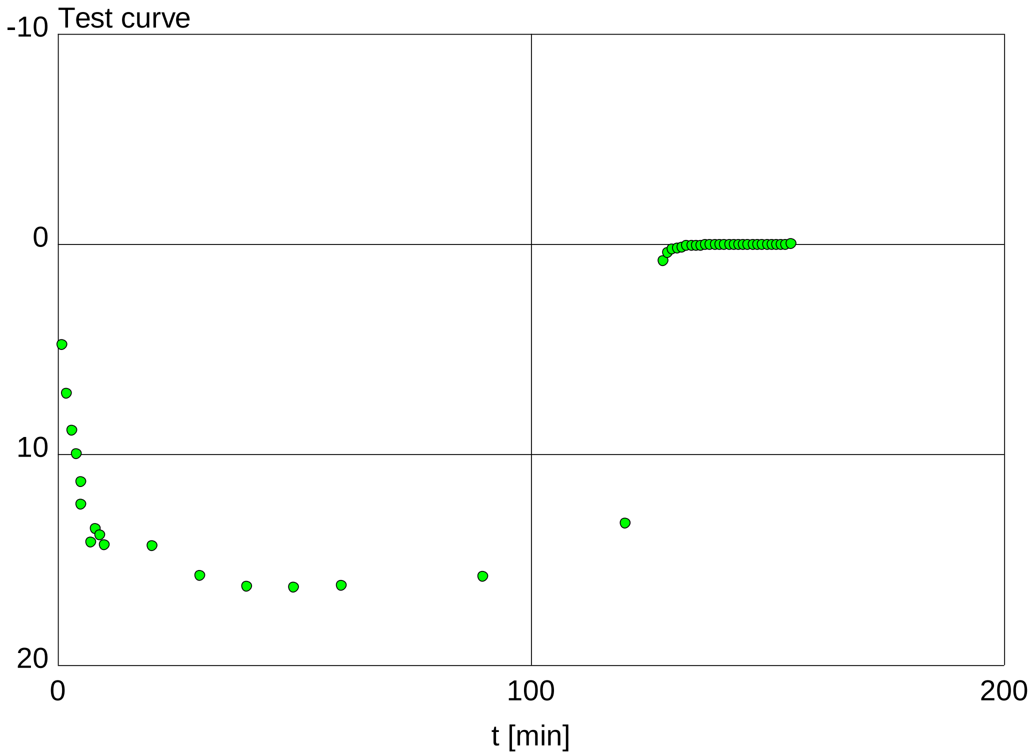


Figure 5-17: Time-Drawdown Plot: Naukluft Park Office

Using Theis method in TPA software (Bardenhagen, 2000) transmissivity is estimated at 10.9 m²/d, (Figure 5-18)

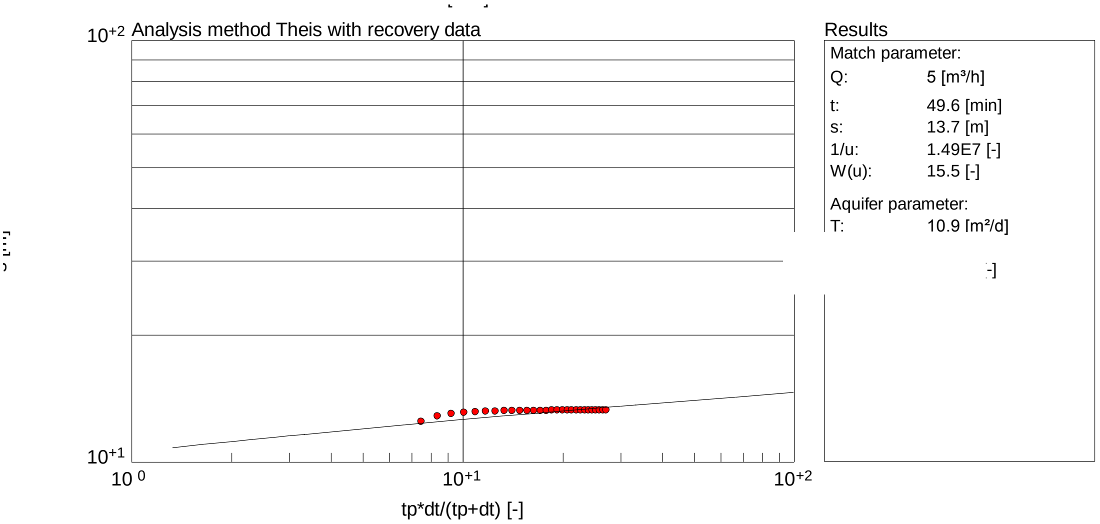


Figure 5-18: Pumping Test Data Analysis Using Theis Method: Naukluft Park Office

Although the pump testing was done over a relatively short period (2 hours), it was still possible to calculate a meaningful transmissivity value. The results indicate medium potential transmissivity. It should be noted that the borehole is very shallow, and if it was drilled deeper higher T-values might have resulted.

At Solitaire Service Station and Lodge, a pumping test was conducted in one of two production boreholes that pump to separate tanks on the establishment. The borehole made available for the study supplied the living quarters and was pumped every four days at 20 m^3/h per day according to the Manager. Borehole depth is roughly 100 m. The borehole taps from the Namib Aquifer in the alluvial of the Tsondab River. The rest water level at the beginning of the test was 74.5 m bgl and after 41 hours of pumping it was lowered to around 96.36 m bgl resulting in a drawdown of 21.86 m.

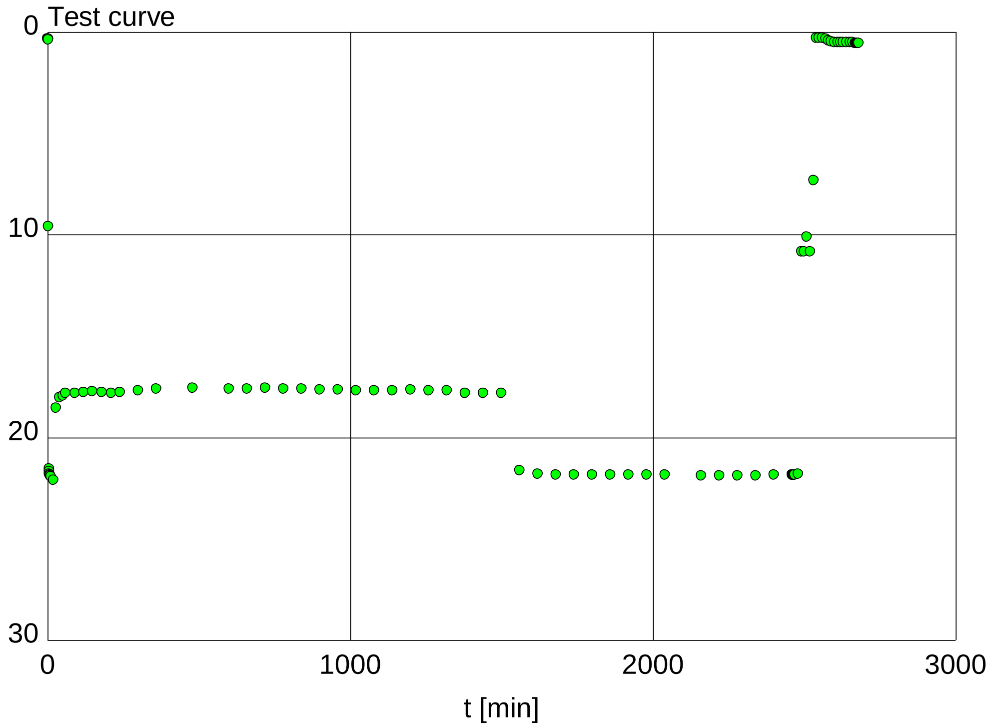


Figure 5-19: Time-Drawdown Plot: Solitaire Service Station and Lodge

Figure 5-19 shows sharp drawdown ten (10) minutes after pumping had started, after which the water level recovered during pumping to around 92 m bgl, it is further observed that after 26 hours of pumping the water level is drawn down to around 96 m bgl, where it stabilizes till recovery started. The borehole recovered in 3 hours and forty minutes after pumping stopped. Recovery is observed to be stepwise. One assumes that the pumping borehole draws from a much larger aquifer because the total drawdown was low for the period of the test. Using Theis method in TPA software (Bardenhagen, 2000) transmissivity is estimated at 23.1 (Figure 5-20).

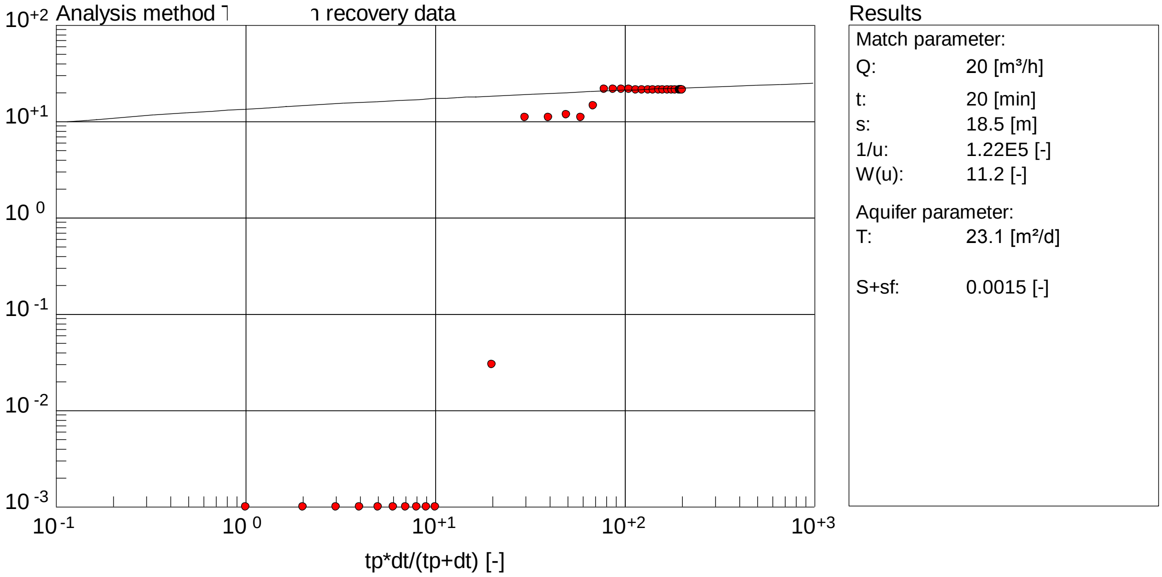


Figure 5-20: Test Pumping Data Analysis Using Theis Method: Solitaire Service Station and Lodge

The Zais is in central part of the Naukluft. Test pumping was conducted on an old well 15 m deep, at the house of the Park Ranger. The immediate lithologies are Nama Group carbonates which are part of the Naukluft Aquifer, beneath which lies the Sole Dolomite. This is an indication that the well taps in the lower-karst of the Naukluft Aquifer. The rest water level was at 9.4 m bgl at the beginning of pumping, lasting for 24 hours at a pumping rate of 5 m^3/h. The water level was lowered to14.84 m bgl; resulting in a drawdown of 5.41 m.

In the time-drawdown plot shown Figure 5-21, a sharp drawdown in the early stages of the test is observed, followed by water level recovery during pumping, stabilizing around 14 m bgl. After the pumping stopped, the water level was observed to continue lowering, taking 19 hours to steadily recover.

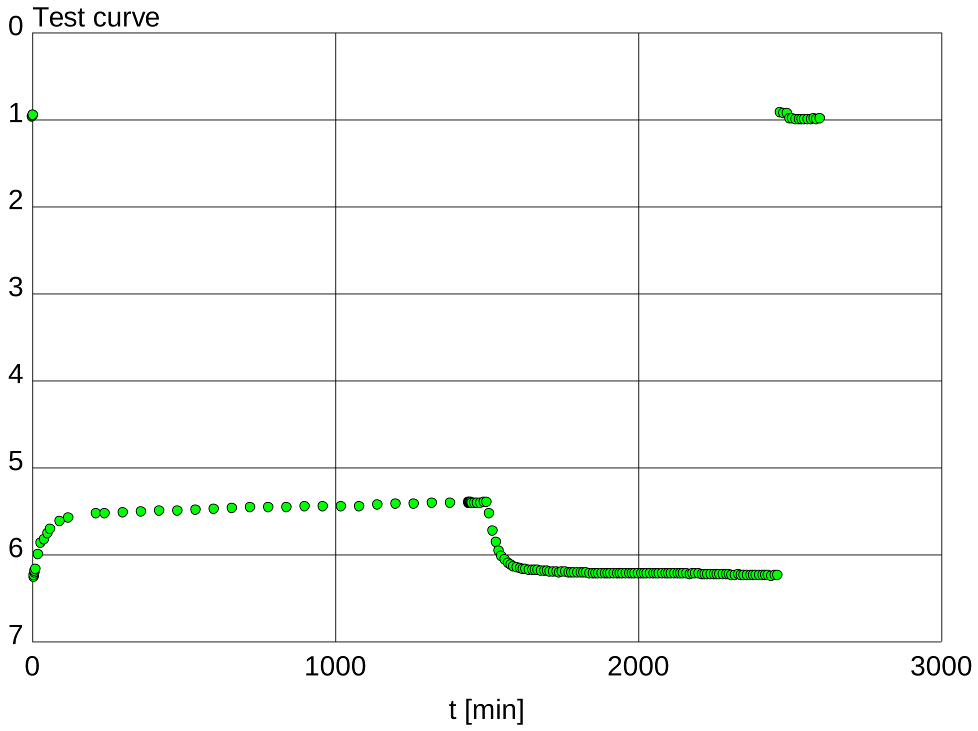


Figure 5-21: Time Drawdown Plot: Zais old well

Using Theis method in TPA software (Bardenhagen, 2000), transmissivity is estimated at 14 m^2/d from different sections of the recovery curve. (Figure 5-22)

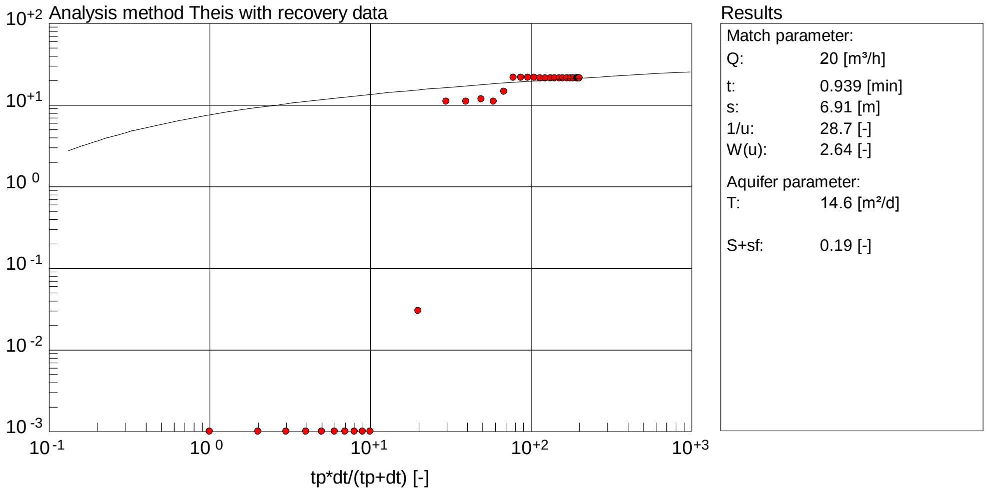


Figure 5-22: Test Pumping Data Analysis using Theis method: Zais Old Well

Table 5-4 summarizes the results of the pumping tests analysis. The results show that the Namib Aquifer has the highest transmissivity and storage coefficient values, followed by the Naukluft Karst Aquifer. The Nama Aquifer is the lowest.

Table 5-4: Summary of Test Pumping Results

Borehole Name	**Longitude**	**Latitude**	**Aquifer**	**Duration**	**Water Level**	**Pumping Rate**	**Drawdown**	**Transmissivity**
	Datum:Schwartzeck			**hr**	**m bgl**	**m^3/h**	**m**	**Theis method m^2/d**
Naukluft Park	16.14603	-24.1569	Naukluft	1 ½	6.72	5	13.28	10.9
Leybank	16.43278	-24.1207	Nama	5	28.42	1.5	12.62	4.1
Zais office	16.15351	-24.0267	Naukluft	25	9.4	5	5.41	14.6
Solitaire	16.01472	-23.8981	Namib	24	74.5	20	21.86	23.1

Test pumping results give transmissivity values of the Naukluft Karst Aquifer to range between 10.9 to 14.6 m^2/d based on the two boreholes tapping the aquifer at Zais and Naukluft Park office. In the dolomite and limestone of the Abenab Subgroup transmissivity of the Abenab Subgroup ranges from 14 to 466 m^2/d established from test pumping of 5 boreholes tapping the aquifer (Bäumle, 2003).

5.6 CONCEPTUAL GROUNDWATER FLOW

The recharge mechanism in the Naukluft Aquifer is rain fed and it is localized as well as rapid. For surrounding aquifers, surface discharge from the Naukluft Karst Aquifer is an added source of recharge. Kazhaei et al, (2003) is of the view that in arid regions, recharge from river beds of ephemeral rivers and subsurface flow in valley bed alluvium in mountainous areas is important; in this statement the author fails to recognise the importance of mountain aquifers and their contribution to recharge of alluvium aquifer, which is the case in the Naukluft. A DEM of the study area in Figure 5-23 clearly shows the orientation of the Naukluft Aquifer in terms of elevation above surrounding aquifers where the aquifer is more elevated and clearly shows the drainage systems of the Tsondab and Tsauchab Rivers from the aquifer.

The Nama and Naukluft Karst aquifers exhibit aquifer-aquitard-aquiclude characteristics due to the nature of the rock types and their location in the stratigraphic column. Both have aquifer horizons interbedded with siltstone, mudstone and shale that may behave as aquicludes; these units have low storage, permeability, hydraulic conductivity and transmissivity. Slate and phylite are aquicludes with no storage or transmission of groundwater.

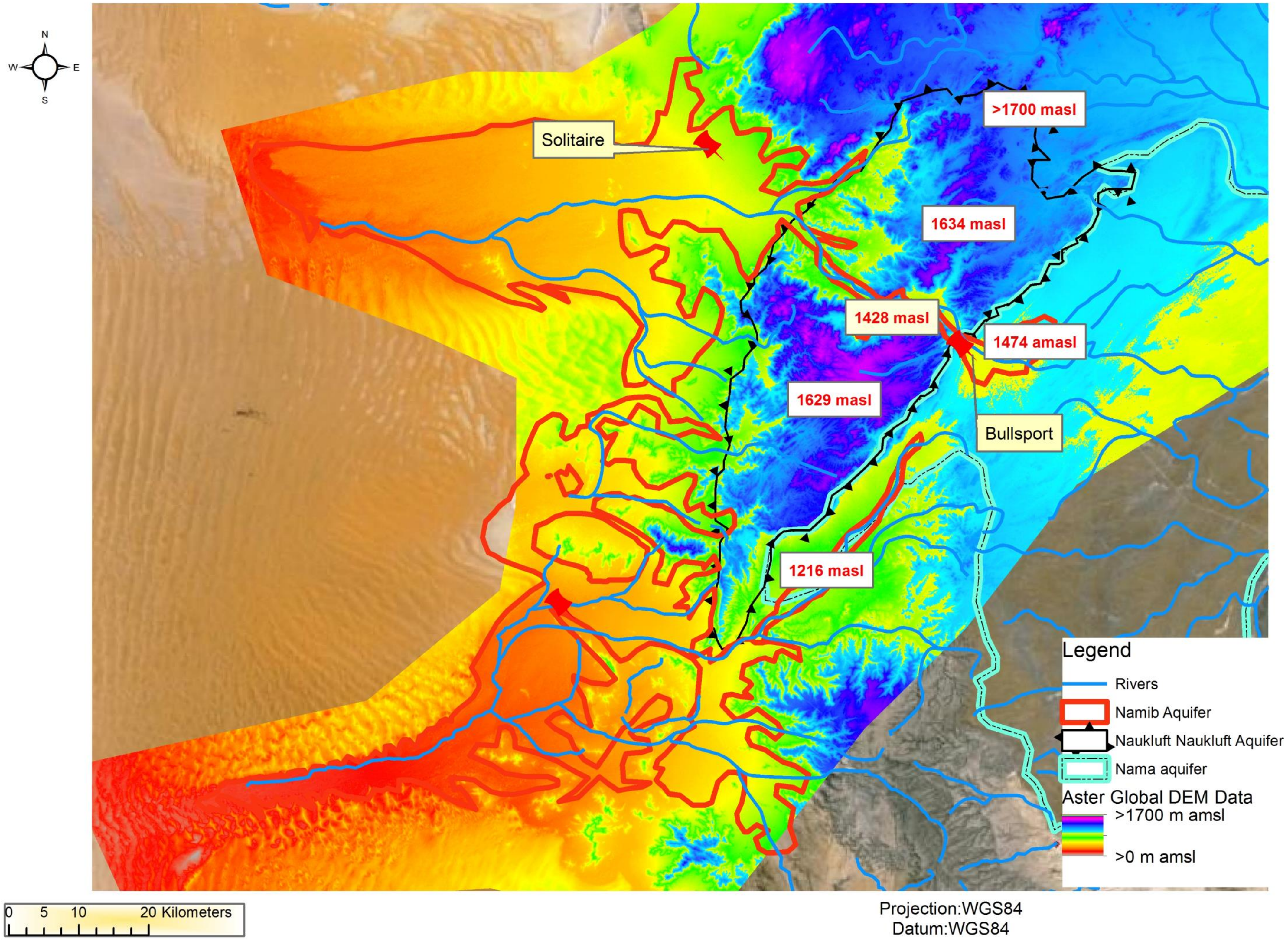


Figure 5-23: 2D Digital Elevation of the Study Area (Source: ASTER Global DEM 90m x 90m Data)

The Namib Aquifer is mainly a primary aquifer system with sands and conglomerates. Domenico & Schwartz (1990) says that un-fractured igneous rocks and metamorphic rocks have the lowest values while gravels and some karst or reef limestone and permeable basalts have the highest values. Work done in the NNC shows that a large number of faults systems occur above the Sole Dolomite, both as thrusts and extensional faults, which features further support that the Naukluft Karst Aquifer to have higher transmissivity than other aquifer in the area.

The Nama Aquifer is dominated by bedded strata, in such a case permeability is greater in the direction of the stratification and smaller in the perpendicular direction to stratification.

For bedded strata; stratigraphic heterogeneity is expected to be one of the main controls of groundwater flow and storage for the whole aquifer system. Cheng and Chen (2007) show that horizontal hydraulic conductivity has the highest composite sensitivity as opposed to vertical hydraulic conductivity. However, in aquitards, vertical hydraulic conductivity has higher composite sensitivity than horizontal hydraulic conductivity. The implication for the Nama Aquifer may be that horizontal percolation of groundwater is more pronounced in aquitards and that vertical percolation of groundwater from the aquifer horizons is limited this could mean that direct recharge through rainfall to the Nama Aquifer is limited and recharge via inflow from the Naukluft Karst Aquifer is more prominent.

The Naukluft Karst Aquifer has bedded strata, however due to nappe emplacement and the angle of emplacement the strata dip to the northwest. One therefore argues that though with heterogeneous strata there is possibility that there is an effect from the dip, which minimizes the effect of heterogeneity on hydraulic conductivity in addition to the network of dissolution features. In this case, hydraulic conductivity is mainly influenced by the extent and intensity of a karst network within the aquifer, interconnectivity, fractures, faulting and lithological contacts. Furthermore, because it is an outcropping aquifer in addition to the factors stated above, the Naukluft Karst Aquifer is more conductive and has high surface discharge than the Nama and Namib aquifers. The same phenomenon is known to control groundwater flow. Quinn et al (2006) concurs by stating that carbonate aquifers typically have complex flow patterns that result from depositional heterogeneities and post lithification fracturing and karstification. Further adding that groundwater flow in such a case is heterogeneous; flow is in all directions. According to White (2007) permeability (porosity) in karst aquifers has three components:

- Matrix permeability of the bedrock itself;
- Permeability produced by fractures (joints, joint swarms, bedding plain partings and some faulting); and
- Permeability due to conduits.

This implies that the Naukluft Karst Aquifer acts as a leaky aquifer where groundwater flows percolates from the upper aquifer through interflow and through flow controlled by the Sole Dolomite and into the lower karst that is within the Nama Group Limestone and in the same manner into the Namib Aquifer. In the case of the Naukluft Karst Aquifer, it is viewed that geological orientation plays a major role in groundwater flow and discharge thereof. One agrees with Dafn et al (2010) that structural folds may direct flow away from general flow gradient. The Naukluft Mountains dip to the northwest but also decrease in altitude towards the south. A two (2) dimensional Digital Elevation Model (DEM) in Figure 5-23 shows that gradual decrease in elevation is to the south of the mountains, however this is not a uniform decrease, as there are sharp variations in high and low attitude points occur that locally control flow. On a large scale, groundwater flow is towards the northwest into the Tsondabvlei and southward into aquifers of the Tsauchab River down to Sesriem (Turner, 2008) as well as to Sossusvlei and into weathered aquifers that form in basement rocks north and south of the mountains. Buffat (2012) alludes to flow in the east towards the Nama Aquifer that is confined in the epi-karst. This eastern flow, though not as well-known as the other two has been investigated using borehole data of the Naukluft Project. Data has shown that water levels drop towards the east in the directions of Elim Farm and from Rietoog towards the Fish River catchment.

Geologic structure due to emplacement in addition to elevation influences groundwater flow. This is supported by Ben-Itzihak & Gurtzman (2005) and White (2007) who state that groundwater flow is influenced by structural folding in a carbonate aquifer. Hydrology of a basin is controlled by the underlying stratigraphy and structure. Figure 5-24 shows spatial distribution of change in hydraulic head and its relationship to geological orientation; and how geological orientation is further correlated to groundwater flow; showing that geological orientation directs water flow towards the structural dip. A clear water divide between the two rivers and groundwater flow is more towards the western direction than to the east meaning that the two water flows do not mix and that there is no flow from the north to the south of the Naukluft Karst Aquifer. Flow is observed to come from the Nama Aquifer towards the Namib Aquifer in the south.

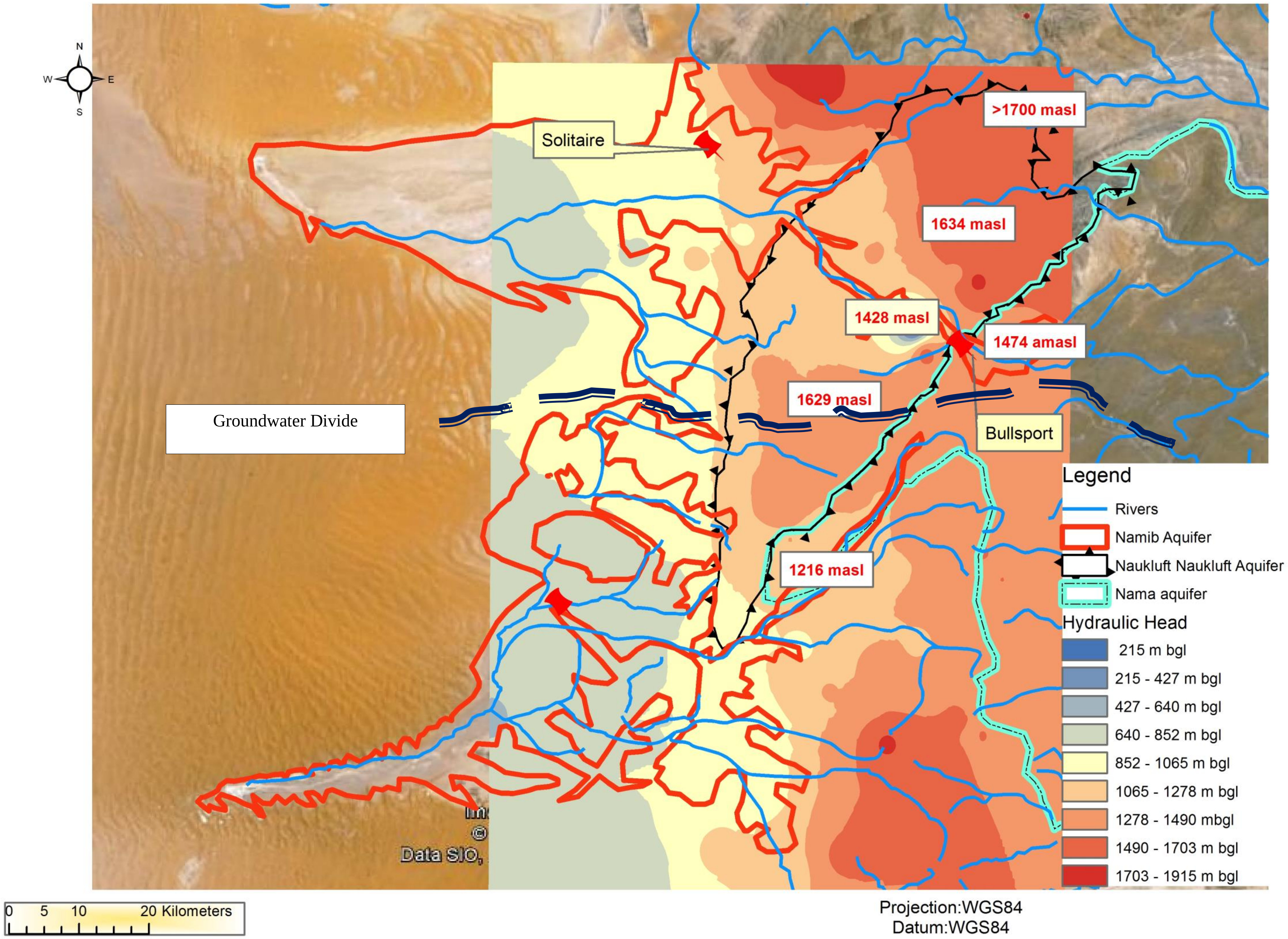


Figure 5-24: Regional Groundwater Contour Map (Data Sourced from: GROWAS)

Within the Naukluft Mountains minimums of nine springs have been identified (Figure 5-25), some of which only discharge water during the rainy season. Springs are a common feature in karst aquifers, indicative of karstification in the aquifer. Karst water only discharges through springs or flows into adjacent alluvium (Raeisi, 2008). In essence, springs are responsive indicators in terms of rainfall or water table lowering. White (2007) notes that because some karsts have rapid response times, spring hydrographs have shown peaks corresponding to individual storms. Increase in spring activity and seepage on rock walls as well as bedding planes during the rainy season are indicative of the high rate of discharge at that period in the aquifer. With such high rates of discharge during the rainy season, groundwater flow is to be limited to the lower karst in the dry season. Water losses due to evaporation are expected to be limited to the Namib Aquifer (Naude, 2010; Buffat, 2012).

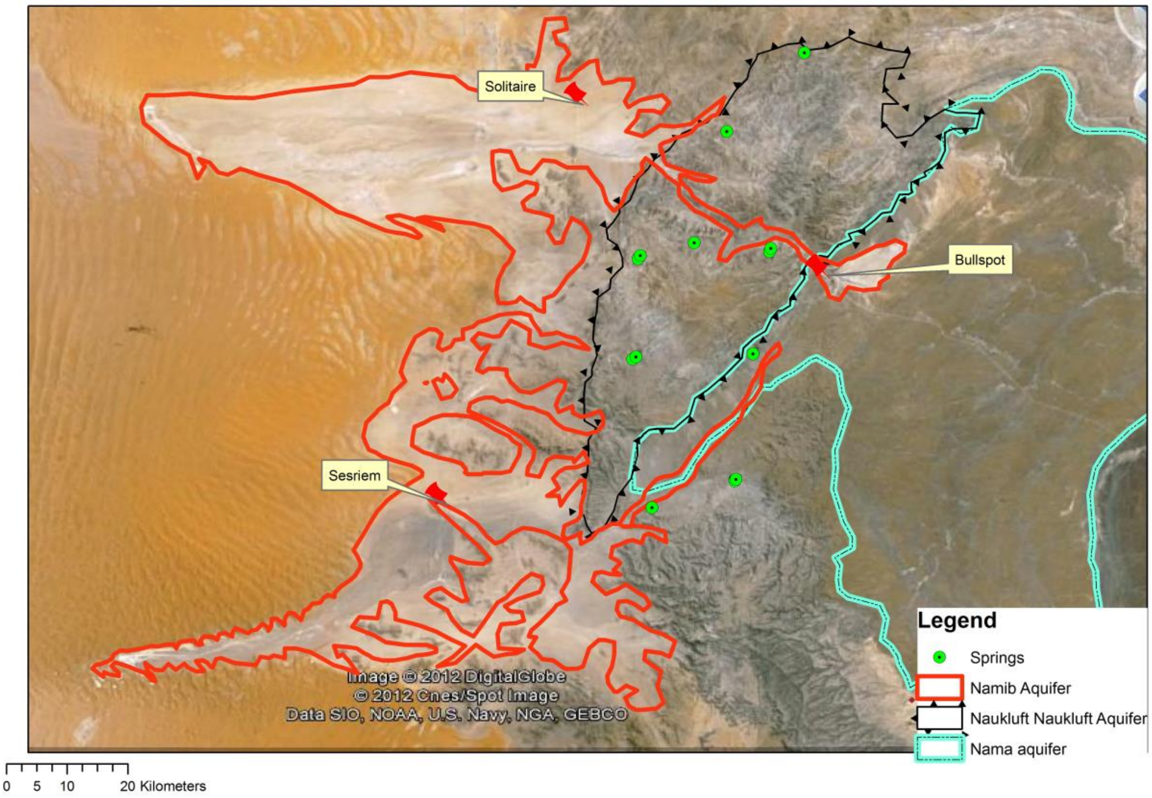


Figure 5-25: Distribution of Springs in the Study Area

Karst carbonate aquifers owe their peculiar properties to the fact that the time scale for chemical reactions between circulating groundwater and carbonate wall rocks is about the same time scale for flow from recharge to discharge points at karst springs. Therefore groundwater chemistry varies with sampling locations and with flow conditions at the time of sampling (Hess & White, 1993). It is due to this variation that classification of different water bodies within the karst aquifer can be made.

A series of hydrochemistry studies have been conducted in the study area looking at various aspects, as a result an insight into the character of the Naukluft Karst Aquifer has been defined. Turner (2008) in his study showed that collected river and creek samples exhibited high pH values compared to groundwater samples. pH was observed to increase progressively towards the west and southwest, relatively low pH values are observed in the northwest. Low pH could be due to acidic plutons or granitic rocks and rhyolites. EC values were highest in groundwater samples while surface and precipitation samples have similar EC values. Highest EC values are observed in the southwestern part and slightly high in the northeast, lowest EC values occur in the northern parts and proximal to the Naukluft Mountains. EC is a good indicator for recharge and discharge areas. High EC may indicate discharge area while low EC indicates recharge zones.

Salinity and TDS are lowest close to the Naukluft Mountains and gradually increase with distance away from the mountains. It is highest in the southwest. Seasonally, Tuner (2008) found that during the dry season lowest pH values occurred in the northeast and east and became higher towards the southwest and western parts. Higher values were recorded in the south. EC values were higher in the dry season compared to the rainy season especially in the south. Salinity was lowest close to the Naukluft Mountains and a seasonal shift was observed in the west and northwest of the mountains in groundwater samples. TDS was highest in the dry season in the southwest and lowest values were recorded in the area close to the Naukluft

Mountains while high TDS and salinity values are observed in the southwest. Groundwater samples had the highest Ca^{2+}, Mg^{2+}, K^+ and Si^{4+} concentrations though no pattern was observed. Groundwater samples also had the highest Na^+ and Cl^- concentrations as well as K^+. A positive correlation between salinity and Na^+, Cl^- and K^+ was observed. Creek and river samples showed similar Ca^{2+}, Mg^{2+}, K^+ and Si^{4+}. Samples collected from the two rivers showed different ionic concentrations. The Tsauchab River had higher EC, TDS and salinity while Ca^{2+} and Mg^{2+} decreased along the river course due to tufa formation (Turner 2008). This could indicate that discharge to the Tsauchab River is slower than to the Tsondab whose orientation is in the general direction of the structural dip of the mountains in addition, the Tsauchab River is thought to be also fed by the epi-karst in the Naukluft Karst Aquifer as well as the Nama Aquifer. Turner (2008) noted that creek samples were more saline than spring samples; this was attributed to evaporation as most springs were found in shadowed areas. Spring samples were more dominated by Mg^{2+} and HCO^{3-} as well as a higher ionic content than creek and river samples. Overall groundwater had higher Ca^{2+} and HCO_3^-. Turner (2008) deduced that there are two groundwater flow regimes that are as a result of the hydraulic gradient and not structurally controlled both flowing from the mountains towards the west and southwest. The hydraulic gradient rises as a result of high recharge while in the east, northwest and southwest are the areas with high abstraction. The gradient in concentration indicates and supports the fact that the Naukluft Mountains receive the most rainfall in the study area. Turner (2008) further states that no seasonal changes in pH of groundwater samples, points to the buffering effect of the aquifer rock, whereas increase in pH values towards the west provided evidence that groundwater flow is towards the west. Findings of this current study show other different influences above and over those described by Turner (2008) in that groundwater and surface flow are highly controlled by geological structure and that the hydraulic gradient is influenced by elevation as indicated by the correlation between structural dip and hydraulic head. This study finds that high abstraction has little influence on regional flow, but rather more on local flow.

The groundwater in the Naukluft Mountains region is confined to carbonate aquifers of the Nama Group (Bernhard, 2009) and those of Damara Sequence that occur above the Sole Dolomite. This suggests that the upper karst of the Naukluft Karst Aquifer stores less volumes compared to the epi karst, although more data would have to be collected on the boreholes that traverse Sole Dolomite; that currently are so few to give reliable information. Raymond (2010) concluded that water levels are often shallow and have a high response to seasonal change, which is directly influenced by local drainage basins around the boreholes, therefore aquifers are vulnerable to contamination. Further Raymond (2010) adds that recharge is local and rapid. This is in fractures, sinkholes and extensional faults.

From the above mentioned a conceptual model of groundwater flow in the study area is proposed, looking at the environmental parameters, aquifer characteristics, possible flow mechanisms and controls as well as the hydrochemistry as given in Figure 5-26, the different aquifers are mapped to the best extent possible with an indication of surface drainage system as visualised in Figure 5-27.

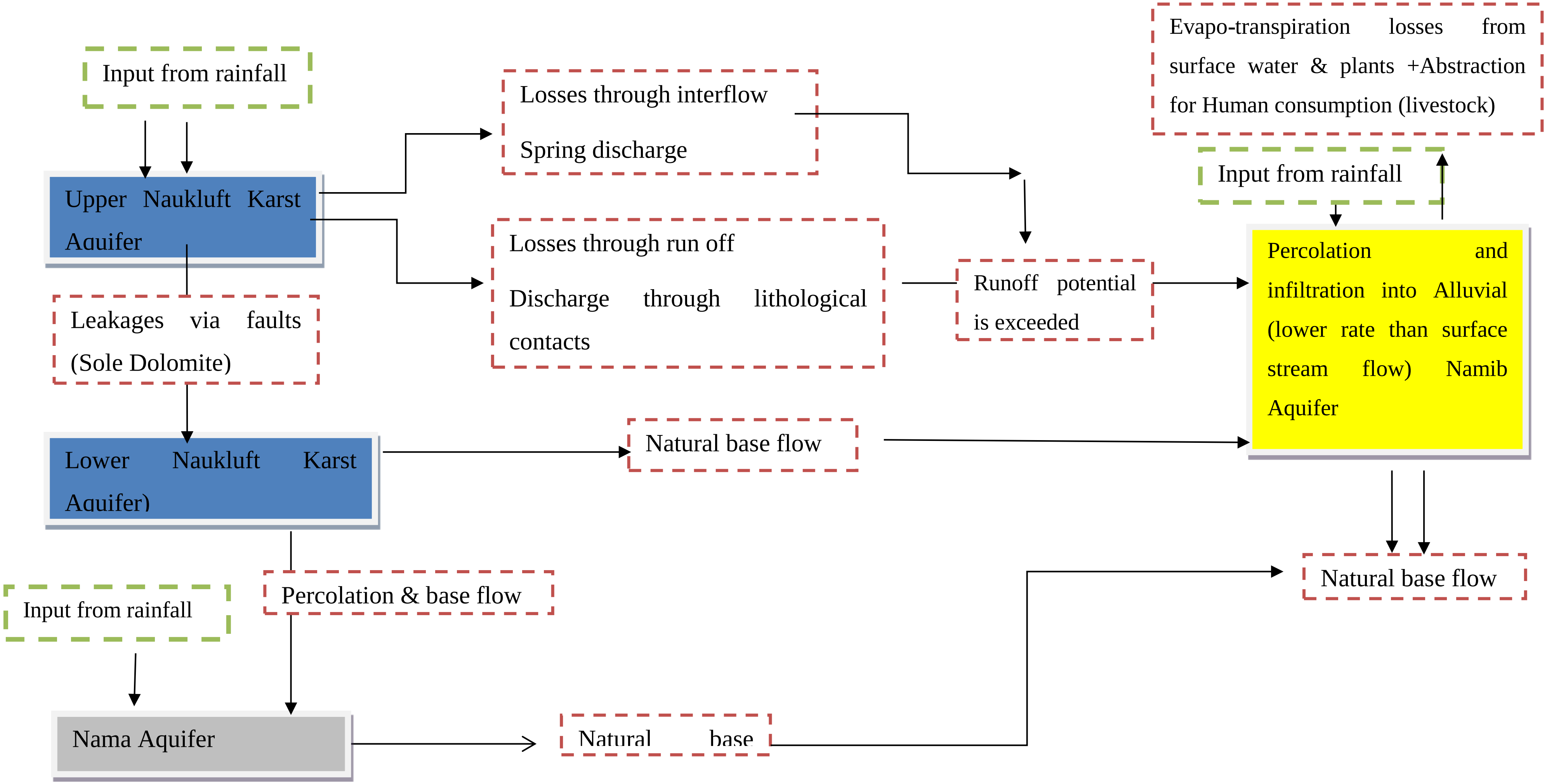


Figure 5-26: Schematic Outline of the Conceptual Groundwater Flow Model.

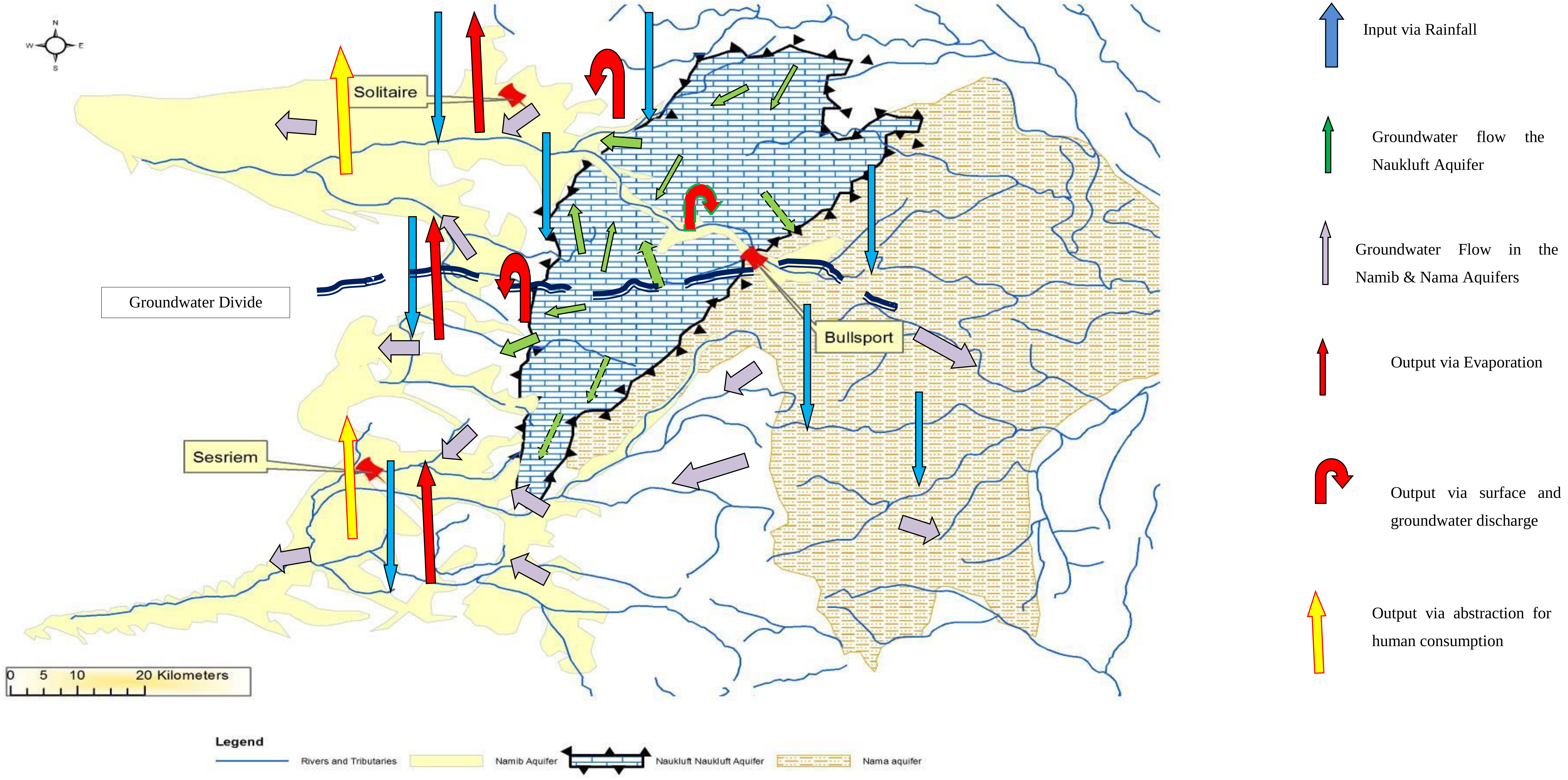


Figure 5-27: 2D Conceptual Groundwater Flow Model Based on Geological and Hydrogeological Results of the Study

CHAPTER 6: STUDY SYNTHESIS

6.1 DISCUSSION

This study classifies three aquifers, based on the lithostratigraphy of the study area; namely:

- ***Namib Aquifer*** confined mainly to the Tsondab and Tsauchab Rivers, whose catchment are the Naukluft Mountains, Mostly composed of gravels, sandstone, conglomerate, dune sand and fluvial sediments which are mainly unconsolidated;
- The ***Nama Aquifer*** is composed of carbonates, sandstone, arenite, conglomerate and grit stone. Deposition cycles are very common within the aquifer; and
- the ***Naukluft Karst Aquifer***, which include formation from older Damaran Formations and those of the younger Nama Group upon which the older rocks are thrust. The aquifer is highly fractured and karstified, the aquifer has further been differentiated between the upper karst and lower karst exhibiting distinct isotope signature. The upper karst is elevated and most of the surface discharge is lost from this part of the aquifer. The lower karst is confined to the Nama Group Limestone.

This study finds that the Sole Dolomite is has significant influence on flow in the aquifer. Separating the upper and lower karst of the Naukluft Karst Aquifer. The Sole Dolomite is a groundwater conduit; its mylonitized surfaces intercept percolating groundwater and discharges to the surface as a spring discharge or surface flow while in the thrust fault zone groundwater flows freely. Extensional fault zones are conduits that allow percolation of groundwater from upper karsts to the lower karst. .

Based on rainfall records spanning 56 years evaluated in the framework of this study rainfall trends have been identified. These records were sourced from farm owners at Bullsport (1950 – 2006), Ababbis and Hauchabfontein start from 2002 and 2005 respectively. A study area average rainfall figure of 170.36 mm/a was calculated from Bullsport data and the national annual average for the area was taken at 200 mm/a. Rainfall trends indicate that a 15-year cycle of good rainfall (above study area and national average rainfall values) is followed by 28-year cycle of below national average rainfall after which a period of good rains starts from 2005 onwards until 2011. The year 2012 was a dry year throughout the NNC, but the carbonate aquifer was discharging from springs, implying that there is a significant amount of fossil water that does not depend on annual rainfall. The lowest rainy season on record is 1995/1996 where only 36.3 mm/a was recorded. Trends on drought show that there is a time lag of 37 years between it and the lowest record of the 1950's (52.2 mm/a). There is a 10 to 20 year time lag between major droughts.

During rainy seasons the Naukluft Mountains area receives the most rainfall; spring discharge, discharge via cavities, and lithological as well as water as a consequence it has a high surface discharge during this time. This study finds that the surface discharge is an added source of recharge to surrounding area especially to the Namib Aquifer as most of the water is channeled through the rivers, water is discharged when the upper karst is saturated and feeds the surface drainage system and springs. Turner (2008) noted that creek samples were more saline than spring samples; this was attributed to evaporation as most springs were found in shadowed areas. This could further indicate that spring water is also more rainwater than groundwater discharge from the upper karst. Percolation of water to the lower karst is via the Sole Dolomite

Large variability between groundwater and precipitation values of stable isotope data implies that only large rainfall events infiltrate the Naukluft Karst Aquifer (Naude, 2010). δ^{18}O and δD values of borehole samples did not change significantly over the sampling season; meaning that groundwater is either an isolated source unaffected by local precipitation and river water, or the groundwater is part of a large water body well mixed and able to homogenize the less negative precipitation isotope values where local recharge occurs in certain parts of the NNC (Naude, 2010). Taking the above premises into consideration, it is suggested that large variability may imply that groundwater recharge is so minimal in the Naukluft Karst Aquifer that it does not have an effect on the groundwater's isotopic signature.

The premise that the Naukluft Mountains area receives the most rainfall is supported by TDS and salinity spatial maps generated by Turner (2008). However, high rainfall received does not equal high recharge to the Naukluft Karst Aquifer as a consequence of high discharge during the rainy season, such that there is little water available for recharge to the aquifer. Recharge is rain fed, local and rapid in the Naukluft Karst Aquifer through direct rainfall. This is similar to results by Allison et al (1985) who investigated local recharge in the Murray Basin in South Australia where calcrete flats with sink holes and sand dunes are adjacent. It was established that major groundwater recharge was driven by high rainfall events that trigger flash flooding and high runoff; further, floodwaters infiltrate the ephemeral river channels recharging local and regional aquifers (Morin et al, 2009).

The Namib and Nama aquifers are recharged by direct rainfall; surface discharge from the mountain area is additional recharge mainly to the Namib Aquifer.

It is expected that recharge to Naukluft Karst Aquifer horizons above the Namib Aquifer occurs first; once saturated recharge from those levels to the surrounding Namib Aquifer occurs. It is observed that even in dry years, the Naukluft Karst Aquifer still discharges in their springs, suggesting that this is a fossil long-lived aquifer.

The results from Naude's (2010) work indicate that surface water contains a significant groundwater signature indicative of 'pre-event' water. The average $\delta^{18}O$ and δD values of surface water in the Naukluft are -5.3 per mil and -35 per mil respectively. These values are significantly closer to the groundwater $\delta^{18}O$ values ($\delta^{18}O$ = -6.7 per mil and δD = -44 per mil) than that of precipitation ($\delta^{18}O$ = -2.2 per mil and δD = -9 per mil). However, the Tsondab

River with no spring supplementing it has more negative $\delta^{18}O$ and δD values than rainwater but less negative values than the other surface waters. This clearly indicates a mix between pre-event and event water. In her work, Naude (2010) deduces that evaporation is not a major process during wet years as results do not change in isotopic composition and that they fall on the Global or Local Meteoric Water Line. However evaporation occurs in the dry years as indicated from the 2008 samples. Naude (2010) explains that this may mean that only large storm events recharge groundwater systems and that the groundwater that has migrated kilometers from higher elevation and higher latitude can have lower δD and $\delta^{18}O$ values than the local precipitation. Lastly, groundwater may have been recharged during ancient pluvial periods when meteoric precipitation had different values and a lower deuterium excess than today. In her study Naude (2010) was not able to determine whether rainfall events sampled recharged the aquifers.

Using the CMB rainfall available for recharge has been estimated to range from of 0.41 to 24.43 mm/a, which translates to 0.24 to 14.24% for both study area and national average rainfall. The figures are within range with what Mangeya et al (2008) estimated by the chloride mass balance method for this area (between Farm Blanzkranz and Solitaire; 23 mm/a was estimated). However the actual recharge is expected to be low due to high losses due to surface discharge Therefore the results of this study are similar to Mangeya et al (2008) and Mainardy (1999) (as quoted by Külls, 2000) estimated for fractured aquifer near Waterberg as well as what Bäumle (2003) modeled for Tsumeb karst aquifer. Both authors show that in fractured aquifers fractures will have higher recharge than what we have estimated. It should be noted that even with this percentage, local available rainfall for recharge is low compared to national available rainfall for recharge estimation. Further, actual recharge is expected to be lower due to significantly high losses through surface discharge.

Large variability between groundwater and precipitation in the signature of stable isotope values implies that only large rainfall events infiltrate the Naukluft Aquifer (Naude, 2010). $\delta^{18}O$ and δD values of borehole samples did not change significantly over the sampling season. Taking the above into consideration, it is suggested that large variability may imply that groundwater recharge is so minimal in the Naukluft Karst Aquifer that it does not have an effect to the groundwater's isotopic signature.

Test pumping results give transmissivity values of the Naukluft Karst Aquifer to range between 10.9 to 14.6 m^2/d based on the two boreholes tapping the aquifer at Zais and Naukluft Park office. The highest transmissivity in the study area is found in the Namib aquifer.

Turner (2008) through his work showed that there are two groundwater flow regimes from the Naukluft Mountains, both generally flowing to the west to the Tsoundab and Soussvlei. The current study concurs with the two flow regimes identified above,. This study shows that the two major flows maybe more complex than previously envisioned. The first flow regime is to the northwest along the Tsondab River and the second flow regime is the southwest following the Tsauchab River.

In this study, a groundwater divide has been identified from the contour map indicating that the flow regimes separate from the center of the Naukluft Karst Aquifer, first into a north to south flow re-directed to the northwest, joined by the south to north flow also re-directed to the northwest along drainage of Tsondab River. The second is from the center there is a more southerly to southwestern flow following the drainage of the Tsauchab River. This implies that no flow from the northern most part of the Naukluft Karst Aquifer reaches the southernmost part of the aquifer.. From the center and south end of the Naukluft Karst

Aquifer there occurs no flow towards the Nama Aquifer implying that there is very limited base flow towards the Nama Aquifer.

A third minor flow regime is identified towards the Nama Aquifer supporting Buffat (2012). There may be zones of mixing between the two flows, emanating from the crystalline basement units, whose signature is diluted by the dominant hydrochemistry of flush floods in the Tsauchab and Tsondab rivers alluvial aquifer systems.

This study shows different influences on groundwater flow compared to Tuner (2008), who concluded that groundwater flow regimes are as a result of the hydraulic gradient and not structurally controlled. Both are flowing from the mountains towards the west and southwest and the hydraulic gradient rises as a result of high recharge while in the east, northwest and southwest occurs the areas with the highest abstraction in the study area. This study shows that groundwater and surface flow are highly controlled by geological structure and that the hydraulic gradient is influenced by elevation as indicated by the correlation between structural dip and hydraulic head. This further reduces flow from the Naukluft Mountains towards the east into the Nama Aquifer.

Groundwater gets older towards the west of the mountains, which Bernhard (2009) accords to be related to the geomorphology of the mountains. This can also be linked to rate of recharge as it is expected that, for the aquifers in the south, recharge is much slower than that of the Naukluft Karst Aquifer, especially in the upper karst where it is rapid. This study finds that high abstraction has little influence on regional flow, but rather on more local flow.

The contour map also shows the Naukluft Mountains Control Groundwater Flow in the study area. Further that some groundwater flow is directed from the Nama Aquifer including the basement highs towards the Namib Aquifer. This indicates that the Nama Aquifer also feeds the Namib Aquifer during dry seasons.

Nama and Naukluft Karst aquifers exhibit aquifer-aquitard-aquiclude character due to rock types and their location in the stratigraphic column. However, the Naukluft Karst Aquifer has higher permeability than the Nama Aquifer. This is because the Nama Aquifer is dominated by horizontal strata consisting of aquifers, aquicludes and aquitards. It is expected that vertical percolation of groundwater is more pronounced in aquifer layers than vertical percolation of groundwater from the aquiclude and aquitard horizons. Therefore, by implication this could mean that direct recharge through rainfall to the Nama Aquifer is limited and recharge via inflow from the Naukluft Karst Aquifer is more prominent. As a result, hydraulic conductivity is expected to be lowered. The structural dip also plays a vital role in the aquifer transmissivity in the Naukluft Karst Aquifer as groundwater flows towards the tilt of the nappes

The Naukluft Karst Aquifer with the same character as the Nama Aquifer is not majorly affected by the dip of strata, due to the presence of and extensive karst network as well as fault zones that are a result of its geologic structure, hence high hydraulic conductivity is expected. The Namib Aquifer as a primary aquifer has the best hydraulic conductivity.

The conceptual model defines that input of water into the system is via rainfall only, more significantly to the Naukluft Mountains. Most of the rainfall received in the mountain area is lost as surface runoff and spring discharge. Most of these losses are in the upper karst of the Naukluft Karst Aquifer discharging mainly to the Namib Aquifer. The Nama Aquifer is receives limited discharge from the mountain area. Since recharge is rapid in the Naukluft Karst Aquifer, there is no influence of evaporation on the aquifer. However evaporation losses are more confined to the Namib Aquifer which is more open to atmospheric interactions. Another major loss for the Namib Aquifer is via abstraction where most of the high density population areas are located in the area.

The Sole Dolomite is a groundwater conduit in the Naukluft Karst Aquifer; it influences losses from the upper karst contributing to spring discharge as well as losses via extensional fault zones into the lower karst. All base flow from the Naukluft Karst and Nama aquifers is fed to the Namib Aquifer, which flows towards the Atlantic Ocean.

Reconnaissance pumping tests were conducted as part of the study to determine transmissivity and storage coefficients in the study area; due to absence of piezometers the storage coefficient was not estimated. It should be noted that test pumping did not include a multi-rate step test due to limitation on data available on the boreholes that were eventually test pumped. Nonetheless results have given better insight into the aquifers.

The results in Table 5-4 show that the Namib Aquifer has the highest range of transmissivity followed by the Naukluft Karst Aquifer and lastly the Nama Aquifer has the lowest, which is a general trend in these aquifers (Domenico & Schwartz, 1990). Further, the hydrographs indicate that the Naukluft Karst Aquifer is more fractured than the Nama Aquifer as dewatering fractures were observed. Once dewatered, recovery was fast.

Water level recovery in the Nama Aquifer was very slow, this speaks to low hydraulic conductivity in this aquifer also indicating that the aquifer has low yielding boreholes.

6.2 CONCLUSION

Four main objectives were set for this study. The summary of the study results discussed above has addressed each objective as follows:

- *To give a summary of the geology and a detailed lithostratigraphy of the study area*

  This study has provided a detailed geology and lithostratigraphy of the study area, thereby providing information on the nature of the formations that form aquifers in the study area;

- *To classify and name aquifers, determine aquifer parameters of the aquifers that are in the study area*

This study classifies three aquifers in the study area, namely the Naukluft Karst Aquifer, Namib Aquifer and Nama Aquifer. Hydrochemistry has been used to show that the Naukluft Karst Aquifer receives the most rainfall and due to the nature of the aquifer high surface discharge is observed.

The aquifer is therefore a more of recharge area for surrounding aquifers than itself as high discharge reduces water available for its own recharge. Recharge is local and rapid via sinkholes, cavities and faults. Cavities, lithological and fault zones act as conduits and discharge zones in addition to springs. The mountains are mainly an outflow area feeding largely the Namib Aquifer;

- *To investigate groundwater flow and the influence of the mountains on groundwater flow in the region surrounding the mountains*

The study has shown that the Naukluft Karst aquifer controls groundwater flow in the study area. Groundwater flow is controlled by structural dip and elevation of the Naukluft Mountains (dipping generally to the west) as a consequence minor groundwater flow is in line with the structural dip as a consequence its more towards Namib Aquifer than the Nama Aquifer.

Three flow regimes have been identified; two in a more westerly direction following surface drainage of the two river systems and minor flow towards the east. A groundwater divide has been identified that shows that the two major flow regimes do not mix. Results of reconnaissance pumping tests have shown that the Naukluft Karst Aquifer is more fractured than the Nama Aquifer. Further, the Naukluft Karst Aquifer has higher transmissivity values than the Nama Aquifer. The Namib Aquifer (alluvial) has the best values in the study area; and

- *To estimate rainfall available for groundwater recharge and define the role that the Naukluft Mountains plays in groundwater recharge in the area*

Using the CMB rainfall available for recharge has been estimated to range from of 0.41 to 24.43 mm/a, which translates to 0.24 to 14.24% for both local and national average rainfall. These results are within range of what Mangeya et al (2008) estimated by for this area between Farm Blanzkranz and Solitaire; a value of 23 mm/a was estimated. Therefore the results of this study are similar to Mangeya et al (2008) and Mainardy (1999) (as quoted by Külls, 2000) estimated for fractured aquifer near Waterberg as well as what Bäumle (2003) modelled for Tsumeb Karst Aquifer. The estimated values for rainfall available for recharge does not account for surface discharge. Figure 5-13 shows that the Naukluft Karst Aquifer generally receives the most rainfall available for recharge; however actual recharge is expected to be low due to high losses due to surface discharge.

6.3 RECOMMENDATIONS

The Naukluft Mountains area has great significance to the hydrogeological system of the study area, in terms of groundwater recharge, discharge and flow control. Though the aquifer is not highly utilized its resource potential is evident, however, the resource is still not quantified.

The current study has shed some light into the hydrogeology of the area by classifying aquifer types, defining aquifer interactions, the role of the Naukluft Karst Aquifer and Sole Dolomite has been elaborated. Its influence on groundwater flow has been described. Estimated groundwater recharge in the area shows that water abstraction in the area is not dependent on recharge, such that the NNC aquifers are more of fossil water systems. The study has further estimated and provided the first aquifer parameters ever for the aquifers in the study area.

Limitations on data in regards to boreholes logs, long-term groundwater level data, and rainfall records from within the study area still need to be addressed to advance future studies. It is therefore recommended to be considered for future investigations as well as set up of infrastructure relating to groundwater in the study areas. Recommendations are made as follows:

- Groundwater level, surface discharge (river gauge) and rainfall monitoring is initiated to monitor seasonal variation and assist in quantification of fluxes;
- More comprehensive pumping test be conducted, first starting with a multi-rate short period step tests that are aimed at stressing the aquifer to determine the best rate at which the long constant discharge test pumping will be conducted;
- Coupled with classification of sub-surface geology as well boundaries; a numerical model of the aquifer should be developed;
- Comprehensive studies on precipitation should continue, there is a need to correlate high rainfall events to recharge;
- Naude (2010) sampled rainfall randomly and rainfall was sampled on the spot when it rained. This limited the interpretation of results as a better correlation of isotopes in precipitation with elevation, seasonality and isotopes from spring, stream, river and boreholes would have been made if sampling stations were established across the study area, therefore it is recommend that a rainfall monitoring and sampling network be initiated for future studies; and
- The CMB method is used to determine how much rainfall remains in the system are based on the data collected from the boreholes, the estimate has not been used to calculate the water budget for the study area as major fluxes could not be quantified. Therefore, results from this study are an indication of baseline estimates, their application should ensure that all limitations are defined. In this study case limitations

are respected as the result is not applied further than just giving the estimation, which was one of the objectives of the study considering only wet deposition values for chloride. Therefore, a more detailed groundwater recharge investigations should still be done.

REFERENCES

Ahmed, S. & Salih, A. (Editors). (2008). *Groundwater Dynamics in Hard Rock Aquifers*: *Sustainable Management and Optimal Monitoring Network Design*. New Delhi. Capital publishing Company.

Andreao, B., Liñán, C., Carrasco, F., Jime'nez de Cisneros, C., Caballero, F. & Mudry J. (2004). Influence of rainfall quantity on the isotopic composition (18O and 2H) od water in the mountains areas. Applied for groundwater research in the yunquera-nieves Karst aquifers (S Spain). *Applied Geochemistry*. 19. 561-574

Allison, G. B. & Hughes, M. W. (1983). The Use of Natural Tracers as Indicators of Soil Water Movement in a Temperate Semi-Arid Region. *Journal of Hydrology*. 60. (1983) 157-173.

Allison, G.B., Stone, W.J. & Hughes, M.W. (1985). Recharge in Karst & Dune Elements of a Semi-Arid Landscape as Indicated by Natural Isotopes and Chloride. *Journal of Hydrology*. 76, 1-25. Amsteterdam: Elsivier Science Publishers

Bäumle, R. (2003). *Geohydraulic Characterisation of fractured rock flow regimes; regional studies in granite (Lindau, Black Forest, Germany) and Dolomite (Tsumeb Aquifers, Northern Namibia), (PhD Dissertation, Universitat Karlsruhe (TH) genehmigte).* Retrieved from the Ministry of Agriculture Water and Forestry

Batisani, N. & Yarnal, B. (2010). Rainfall Variability and Trends in Semi-Arid Botswana: Implications for Climate Change Policy. *Applied Geography*. 30(4), 483-489.

Barbieri, M., Boschetti, T., Petitta, M. & Tallini, M. (2005). Stable isotopes (^{2}H, ^{18}O and ^{87}Sr/^{86}Sr) and Hydrochemistry Analysis in a Karst Aquifer (Gran Sasso Central). *Applied Geochemistry.* 20, 2063-2081.

Bardenhagen, I. (2000). Test Pumping Analysis for Fractured and non-Fractured Aquifers (software)

Bazuhair, A.S. & Wood, W.W. (1996). Chloride Mass Balance Method for Estimating Groundwater Recharge in Arid Area: Example from western Saudi Arabia. *Journal of Hydrology*. 186, 151-159.

Ben-Itzhak, L.L. & Gurtzman, H. (2005). Groundwater Flow Along and Across Structural Folding, An Example from Judean desert, Israel. *Journal of H*ydrology. 312 , 51-61.

Behr, H.J., Arendt, H., Porada, H. & webber, K. (1983). The Sole Dolomite at the Base of the Naukluft Nappe Complex. *Geological Society of south africa, special publication.* 11, 183-197.

Bernhard, C. (2009). *Mean Residence Time of the Groundwater in the Naukluft Mountains Aquifer: Evaluation based on carbon isotopes and perspective for water management in Namibia* (Mashers thesis. University of Lausane, Switzerland).

Bear, J., Beljin, M.S. and Ross, R.R. (1992). Fundamentals of Groundwater Modelling. *EPA Groundwater Issue.* 540/s-92/005.

Biesheuvel, A. & Hemker, C.J. (1993). Groundwater Modelling and GIS: Integrating Micro-FEM & ILWIS. *HydroGIS.*: *Application of Geographic Information Systems in the Hydrologya and Water Resources* (proceeding from the Vienna conference, April 1993, IAHS publication 211) 93,289-296

Bittner Water Consult. (2004). *Demarcation of Water Basins on a National Level (Technical Report).* Retrieved from the Ministry of Water Affairs and Forestry.

Bodin. J., Ackerer. P., Boisson, A., Bourbiaux. B., Burel. D., de Druezy. J-R., Delay. F., Porel, G. & Pourpap, H. (2012). Predictive Modelling of Hydraulic Head Responses to

Dipole Flow Experiments in Fractured/Karstified Limestone Aquifer: Insight from a Comparison of Five Modelling Approaches to Real Field Experiments. *Journal of Hydrology*. 454-455, 82-100.

Boyer, D., Cole, J. & Bartholomae, C. (2000). Southwestern Africa: Northen Benguela Current Region, *Marine pollution Bulletin*, 4(1-6), 123-140. Retrieved from Springerlink Online Research Database

Buffat, A. (2012). *Nitrate Isotopic Study in Waters from the Naukluft Mountains, Namibia*. (Masters in Biogenscience Thesis, Universities of Neuahatel and Lausane, Switzerland)

Cheng, C. & Chen, X. (2007). Evaluation of methods for determination of hydraulic properties in an aquifer-aquitard system hydrologically connected to a river. *Hydrogeology Journal*. 15(4). 669-678. Retrieved from Springerlink Online Research Database

Christelis, G. & Struckmeier, W. (Eds) (2001). *Groundwater in Namibia: An explanation to the hydrogeological map (1st Ed).* Windhoek: John Meinert Printing.

Dafn, E., Burg, A. & Gvirtzman, H. (2010). Effects of Karst and Geological Structure on Groundwater Flow: The Case of Yarqon-Taninim Aquifer, Istael. Journal of Hydrology. 389, 260-275. Retrieved from Elsevier Online Research Database.

Deer, W.A, Howie, R.A. & Zussman, J. (1996). *An introduction to rock forming minerals*. London: Longman Group Limited.

De smedt, F. (2011). Analytical Solution for Constant Rate Pumping Test in Fissured Porous Media with Double-Porosity Behaviour. *Transport in a Porous Media*. 88, 479-489.

Domenico, P.A. & Schwartz, F.W. (1990). *Physical and Chemical Hydrogeology, 2nd Edition*. New York: John Wiley & Sons, Inc.

Esri, (2010) Arc-GIS 10 Software.

Faber, C. (2009). *Silica Gel in Nappe-Boundng Faults: Naukluft Nappe Complex, Namibia: Geologic Record of Dynamic Weakening During Continental Orogenisis.* (Bachelor of Science Honors Degree Thesis, University of Cape Town, South Africa).

Fleury, P., Plagnes, V. & Bakalowicz, M. (2007). Modelling of the Functioning of Karst Aquifers with a Reservoir Model: Application of Fontaine de Vaucluse (south of France). Journal of Hydrology. 345, 38-49)

Guan, h., Love, A. J., Simmon, C. T., Makhnin, O. & Kayaal, A. S. (2010). Factors Influencing Chloride Deposition in a Coastal Hilly Area and Application to Chloride Deposition Mapping. *Hydrology and Earth System science*. 14, 801-813.

Gresse, P.G. & Germs G.J.B (1993). The Nama foreland Basin: Sedimentation, Major Unconformity Bounded Sequences and Multisided Active Margin Advance. *Precambrian Research,* 63, 247-272. Amsterdam: Elsevier Science Publishers

Haitjema, H. M. (1995). *Element Modeling of Groundwater*. California. Academic Press Inc.

Hess, J.W. & White, W.B. (1993). Groundwater Chemistry of Carbonate Karst Aquifer, south kentucky, USA. *Applied Geochemistry*. 8, 189-204.

Heath, R.C. (1983). *Image of Secondary Porosity*. USGS paper 2220.

Ingebritsen, S., Sanford, W., Neuzil, C., 2006. *Groundwater in Geologic Processes, 2nd ed*. Cambridge University Press

Herczeg, A.L., Leaney, F.W.J., Stadter, M.F., Allan, G.L. & Fifield, L.K. (1997). Chemical and Isotopic Indicators of Point Source Recharge to a Karst Aquifer, South Australia. *Journal of Hydrology*. 192, 271-299.

Huston, J. (2007). Recharge to groundwater in Turi Basin, Northern Chile: An evaluation based on tritium and chloride mass balance techniques. *Journal of Hydrology*. 334, 534-544.

Jacobson, P.J. & Jacobson, K.M. (2012). Hydraulic Controls of Physical and Ecological Processes in Namib Desert Ephemeral Rivers: Implications for Conservation and Management. *Journal of Arid Environment Conservation and Management*. 1- 14. Retrieved from Elsevier Online Research Database.

Joint Venture Namibia. (2010). *Integrated Water Resource Management Plan for Namibia: The Assessment of Resources Potential and Development Needs.* (Thematic Report2). Retrieved from the Ministry of Water Affairs and Forestry.

Kittan, Z. (1997). Environmental Isotope Study of the Major Karst, Springs in Damascus Limestone Aquifer System: Case of the Figeh and Barada Springs. *Journal of Hydrology*. 193, 161-182.

Klock, H. (2001). *Hydrogeology of the Kalahari in North-estern Namibia with Special Emphasis on Groundwater Recharge, Flow Modelling and Hydrochemistry*. Doctorate Thesis. Julius-Maximilian University of Würzburg.

Kollet, S.J. & Zoltnik, V.A. (2005). Influence of Aquifer Heterogeneity and Return Flow on Pumping Test Data Interpretation. *Journal of hydrology*. 300, 267-285.

Kovács, A., Perrochet, P., Király, L. & Jeannin, P-Y. (2005). A quantitative method for the characterisation of karst aquifers based on spring hydrograph analysis. *Journal of Hydrology*. 303. 152-164.

Kruseman, G.P. & de Ridder,N.A. (1991). *Analysis and Evaluation of Pumping Test Data, 2nd edition (Completely Revised)*. Wagenigen: International Institute for Land Reclamation and Improvement

Külls, C. (2000). *Groundwater of the North-western Kalahari, Namibia; Estimation of the Flow Systems*. Doctorate Thesis. Julius-Maximilian University of Würzburg

Leven, C. & Dietrich, P. (2006). What Information Can we get from Pumping Tests?- Comparing Pumping Test, Configurations using Sensitive Coefficients. *Journal of Hydrology*. 319, 199-215.

Lerner, D.N., Issar, S. & Simmer, I. (1990). Groundwater Recharge: A guide to understanding and estimating recharge. International contributions to hydrogeology. 8.

Long, A.J. & Putnam, L.D. (2004). Linier Model Describing Three Components of Flow in Karst Aquifers. *Journal of Hydrology*. 296,254-270.

Ludwig, R. and Schineider, P. (2006). Validation of Digital Elevation Models from SRTM X-SAR for Application in Hydrogeologic Modelling. *Journal of Photogrammetry and Remote Sensing*. 60, 339-358.

Mangeya, P., Mapani, B., Miller, J., Rowe, C., Naude, K., Terblanche, A. & Turner, S. (2008). *Dynamics of groundwater flow in the Naukluft Nappe Complex and the Nama Group in the Naukluft area of Namibia* (abstract). 9th Waternet/WARFSA/GWP Symposium. Johannesburg.

Mapani, B., Miller, J.A., Rowe, C., Kambinda, W.N., May, F., Naude, K., Terblanche, A. & Turner, S. (2009). Groundwater Dynamics, Flow and Aquifer Behaviour in the Naukluft Nappe Complex and Nama Group in the Naukluft Area of Namibia. *Waternet 10th Symposium.* (Abstract). Etembe, Uganda.

Mazor, E. (2004). *Chemical and Isotopic Groundwater Hydrology*. Third edition. New York. Marcel Dekker.Mendelsohn, J., Jarvis, A., Roberts, C. & Robertson, T. (2002). *Atlas of Namibia: A Portrait of the Land and its People*. Cape Town. David Philips Publishers.

Miller, McG.R. (2008). *The Geology of Namibia Vol.2 .Neo-Proterozoic to Lower Palaeozoic, Volume 2*. Windhoek: Geological Survey of Namibia .ISBN 978-0-86976-732-0.

Miller, J.A., Viola, G. & Mancketelow, N.S. (2008). Oxygen, Carbon and Strontium Isotope Constraints on the Mechanisms of Nappe Emplacement and Fluid–Rock Interaction along the Subhorizontal Naukluft Thrust, Central Namibia. *Journal of the Geological Society*, 165, 739-753.

Miyak, N., Kohsaka, N. & Ishikava, A. (2008). Multi-Aquifer Pumping Test to Determine Cut-off Well Length for Groundwater Flow Control during Site Excavation in Tokyo, Japan. *Hydrogeology Journal.* 16, 995-1001

Morin, E., Grodek, T.G., Dahan, O., Benito, G., Külls, C., Jacoby, Y., van Langen Hove, G., Seely, M. & Enzil, Y. (2009). Flood Routing in Alluvial Recharge along the Ephemeral Kuiseb River, Namibia. *Journal of Hydrology*. 368(1-4), 262-275.

Modarres, R. & da Silva, V.dP. (2007). Rainfall in Arid and Semi-Arid Regions of Iran. Journal of Arid Environments. 0(2), 344-355.

Naude, K. (2010). *A Stable Isotope Study of the Hydrogeological Systems of the Naukluft Region in Namibia.* Masters Degree in Geology Thesis, University of Cape Town, South Africa).

Peck, H. (2010). *The Preliminary Study of the Stampriet Transboundary Aquifer in the South East Kalahari/Karoo Basin*. (Masters in Hydrogeology Thesis, University of the Western Cape, South Africa)

Pettijohn, F.J. (1975). *Sedimentary Rocks,* 3rd Edition. New York: Harper and Row publishers.

Praamsma, T., Navakowski, K., Kyser, K. & Hall, K. (2009). Using Stable Isotope and Hydraulic Head Data to Invest Groundwater Recharge and Discharge in a Fractured Aquifer. *Journal of Hydrology*. 366, 35-45.

Quinn, J.J., Tomasko, D. & Kuiper, J.A. (2006). Modeling Complex Flow in a Karst Aquifer. *Sedimentary Geology*. 184, 343-351. Retrieved from Elsevier Online Research Database.

Raeisi, E. (2008). Groundwater Storage Calculation in Karst Aquifers with Alluvium on no Flow Boundaries. *Journal of Cave & Karsts Studies*. 70(1), 62-70.

Raymond, C. (2010*). Nitrate and sulphate isotopic study in surface and groundwaters from the Naukluft Mountains, Namibia* (Masters Degree Thesis, Institute of Mineralogy and Geochemistry. University of Lausanne).

Rowe, C., Fagereng, A., Miller, J.A. and Mapani, B. (2012). Signature of coseismic decarbonation in dolomitic fault rocks of the Naukluft Thrust, Namibia. *Earth and Planetary Science Letters, volume 333-334, 200-210.*

Shard, V.N., Kutothe, R.S., Sena, D.R., Pande, V. C. & Tiwan, S. P. (2006). Estimation of Groundwater Recharge from Water Storage Structures in Semi-Arid Climate, India. *Journal of Hydrology*. 329, 224-243.

Sylvester, F. (2009). *The site, shape and Style of Continental Detachment: Fault Geometries and Britle-Ductile Behavior of the Naukluft Thrust Namibia* (Bachelors of Science Honors Degree Thesis, The University of Cape Town. South Africa).

Tilahun, K. (2006). Analysis of Rainfall, Climate and Evapo-Transpiration in Arid and Semi-Arid Regions of Ethiopia Using Data of over the Last Half a Century. *Journal of Arid Environments.* 64(3), 474-487.

Turner, S. (2008). *Geochemical analyses of the ground and surface water in the Greater Naukluft Region of south-western Namibia* (Bachelors of Science Honors Degree Thesis, The University of Stellenbosch).

Vogel, J. (1989). Evidence of past climate change in the Namib Desert. *Palaeogeography, Palaeoclimatology, Palaeoecology* 70, 366-366.

Weber, K. & Ahrendt, H. (1983). Mechanisms of Nappe Emplacement at the Southern Margin of the Damara Orogen (Namibia). *Tectonophysics.* 92, 253-274. Amsterdam: Elsevier Scientific Publishing Company.

Winker, F. (2010). *Groundwater Model of the Swakop River Basin, Namibia*. Diploma Thesis. Institute of Hydrology Freiburg

Witherspoon, P. A., Wang, J. S. Y., Iwai, K. & Gale, J. E. (1979). *Validity of Cubic Law for Fluid Flow in a Deformable Rock Fracture* (Reort repared by Lawrence Barkeley Laboratory under the University of California).

White, W.B. (2002). Karstic Hydrology: Recent Developments and Open Questions. *Engineering Geology*. 65, 85-105.

White, W.B. (2007). A Brief History of Karst Hydrogeology. Contributions of the NSS, *Journal of Cave & Karst Studies*. 69(1), 13-26.

Xu, Y. & Beekman, H.E. (Editors). (2003*). Groundwater Recharge Estimation in Southern Africa*. Cape Town: UNESCO Paris

Xu, Y. & Braune, E. (2010). *Sustainable groundwater resources in Africa: water supply and sanitation environment*. UNESCO International Hydrological Programme. Paris.

Zaman, M.A., Rahman, A. & Hddad, K. (2012). Regional Flood Frequency Analysis in Arid Regions: Case Study Australia. *Journal of Hydrology*, (accepted transcript).

Zhou, Y. & Li W. (2011). A Review of Regional Groundwater Flow Modelling. *Geoscience frontier*. 2(2), 205-214.